WATER RELATIONS OF SOME LYSIMETER-GROWN WILDLAND PLANTS IN SOUTHERN CALIFORNIA

by

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Upper Darby, Pa. June, 1974

Library Abstract:

Patric, James H.

1974. Water relations of some lysimeter-grown wildland plants in southern California.

One of the world's largest lysimeter installations was operated from 1937 until 1960 near Los Angeles, California. The lysimeters were covered with excelsior, grass, and wildland species (grass, chaparral, and coulter pine) for 3, 6, and 14 years respectively. Evapotranspiration from bare soil was less than from grass, and from grass was less than from woody vegetation. Diminished growth by lysimeter plants and disproportionately large surface runoff suggest that these results must be applied most cautiously to forested watersheds. Recently developed research methods probably afford more reliable knowledge of plant-water relations at considerably less cost.

Key Words:

Chaparral
Coulter pine
Evaporation
Evapotranspiration
Grass
Interception loss
Lysimeters
Plant-water relations
Rainfall
San Dimas Experimental Forest
Seepage
Soil-water relations
Southern California
Surface runoff
Transpiration
Watershed management

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ACKNOWLEDGMENTS

Obviously, I cannot acknowledge all who have helped in so many ways to make possible this report of research on the San Dimas lysimeters, likely the last and most comprehensive such research to be attempted. I must, however, specifically recognize Dr. Martin Zimmermann (Charles Bullard Professor of Forestry, Harvard University and Director, Harvard Forest) for providing funds and facilities, and Mr. Joseph Mawson (Assistant Professor of Forestry, University of Massachusetts) for computer programming. Without their contributions, this study could not have been undertaken. But to all who contributed in whatever way, my sincerest thanks.

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ABSTRACT

Twenty-six concrete lysimeters (5 mil-acre surface, 6 feet deep) were constructed 1934-38 near Los Angeles, California. All were filled with uniform soil. Five "unconfined" lysimeters (in residual soil) were constructed nearby and refilled with the uniform soil to demonstrate wall effects on plant water use. The installation's primary purpose was to provide measurements of soil moisture use by selected chaparral species, but some lysimeters were planted to coulter pine and native grasses. One was maintained with no vegetation. Soil in all lysimeters settled for 3 years under a cover of excelsior. Then all but the bare lysimeter were planted to grass for a 5-year calibration period, followed by the final planting to wildland species in 1946. Active research ceased in 1960 when the installation was severely damaged by wildfire.

Rainfall, surface runoff, and seepage were measured from 1938 until 1960. Rainfall was uniform over the installation. Surface runoff from vegetated large lysimeters was about 100 times greater than on nearby slopes with deeper and sandier soil; surface runoff from the unconfined lysimeters was about 10 percent less than from the large lysimeters. Only grass provided a regular seepage yield, even in dry years. Evaporative losses were computed for large lysimeters as ET=Precipitation - (surface runoff + seepage). Evaporative losses were least (7 inches, more or less) on bare soil, and intermediate (12 inches, more or less) on grass. Wildland species evaporated whatever soil moisture was available, with annual losses ranging from 9 inches in driest years to about 30 inches in the wettest year. Soil moisture was measured regularly with Colman units after 1952. Soil moisture use by any given species was uninfluenced by lysimeter walls until rain absorption exceeded the water-retaining capacity of large lysimeter soils. Thereafter, more soil moisture was retained in deeper soils of the unconfined lysimeters and plant-water use on them increased accordingly. By the end of each growing season,

large lysimeters containing chamise and buckwheat retained about 1-inch less soil moisture than did those growing scrub oak and coulter pine. Plant-water use approached evaporative potential whenever soil moisture was high, but use-rates declined as soils dried. Root confinement reduced plant growth, with smallest plants least affected. Reduced growth did not measurably decrease plant-water use.

Lysimeters were evaluated as sites for comparing plant-water relations of wildland plants. It was concluded that other approaches should provide more representative, less expensive data on soil moisture use and other water relations of wildland plants, particularly for large, woody plants.

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INTRODUCTION

PROLOGUE

> There is one branch of research which is of the utmost importance in reference to these questions, but which, from the great difficulty of direct observation upon it, has been less successfully studied than almost any other problem of physical science. I refer to the proportions between precipitation, superficial drainage, absorption, and evaporation. Precise actual measurement of these quantities upon even a single acre of ground is impossible; and in all cabinet experiments on the subject, the conditions of the surface observed are so different from those which occur in nature, that we cannot safely reason from one case to the other. (Marsh 1864).

An ambitious program of forest water relations research began almost four decades ago at the San Dimas Experimental Forest in southern California (Sinclair et al. 1958). A lysimeter installation, perhaps the world's largest, was an integral part of that program. From 1957 to 1960 I was a young research forester at least nominally in charge of lysimeter studies. I left the San Dimas Forest early in 1960, with little more than a superficial report (Patric 1961a) to show for the experience. Soon afterward, wildfire swept the forest, severely damaging the lysimeters. This fire drastically altered the course of research at San Dimas (Hopkins et al. 1961). Interest in the lysimeters waned and ultimately the data from 23 years of intensive plant-water relations research were interred at a federal records center.

Although the people once involved in this research now are scattered, their records remain a veritable gold mine of measurements and unpublished reports. Harvard University's Bullard Fellowship gave me the long-sought opportunity to delve more deeply into these records, this time unencumbered by other priorities. I have disinterred the labors of my predecessors and have drawn freely from them. If errors or misinterpretations have crept through, the fault is mine.

BACKGROUND

The perennial problem of water scarcity in the American Southwest needs no restatement here. Suffice it to say that, during the years between World Wars I and II, southern Californians looked to their region's 5 million acres of chaparral as a potential source of water to help meet needs even then exceeding the more readily available supplies. A fundamental consideration was: "Do some chaparral species use more water than others?" If so, then methods would be devised to favor those species requiring least water and to eliminate the most extravagant water users from chaparral-covered watersheds. The water thereby diverted from "waste" by economically valueless plants would somehow be collected and redistributed to help satisfy ever-increasing human needs.

At about the turn of the century, there had been tremendous interest in the relations of forests to water resources. Some of the then-current ideas on this relationship were remarkably consistent with today's concepts. Chittendon (1908), for example, suspected "that forests decrease somewhat the total runoff from watersheds great and small". A storm of reaction, both pro and con, followed this pronouncement, most of it unsupported by data. Although a study from Switzerland (Engler 1919) tended to support Chittendon's view, evidence more acceptable to the scientific community was slow to develop. Later, clearcutting of forests (Bates and Henry 1928) and burning of chaparral (Hoyt and Troxell 1934) were found to cause modest streamflow increases under semi-arid climate. Developing knowledge of water use by trees led Kitteredge (1937) to speculate that changing the density, size, or composition of forest in a more humid climate could increase annual streamflow even more, possibly as much as 3 inches annually.

There was a surprising amount of evidence to support such speculation. Kitteredge's (1948) subsequent review defined a "state-of-the art" upon which research in forest-water relations was seeking to build about 30 years ago. Many of the contributory studies had been done in California, some on lysimeters (Kotok 1930). In fact, interest in lysimeter research probably peaked at about this time, even though results of plant-water studies in them were subject to well-known reservations. Notable among these were the disruption of normal soil structure and impeded drainage (Kohnke et al. 1940). These authors nevertheless concluded that "many questions concerning hydrology can be answered by the correct use of lysimeters".

During the 1930s, research on forest-water relations, theretofore scattered about southern California, became centered in the Angeles National Forest. This research center, the San Dimas Experimental Forest (Kraebel and Sinclair 1940), is ideally located for such studies. Lying close to metropolitan Los Angeles, it is in the foothills of the San Gabriel Mountains and representative of much brushland in southern California. And it is on a watershed providing a major natural water supply to the San Gabriel Valley. One of the forest's research objectives was to learn how vegetation influenced the disposition of rain falling on chaparral-covered land. Lysimeters were to play a featured role in this research; on them, water relations of selected chaparral species would be compared under conditions of minimum environmental variation.

Unemployment was rampant when this program of watershed management research was undertaken. These were years of the Great Depression, and full advantage was taken of then-current programs of public works. A large part of the energies of personnel in a CCC camp, a WPA project, and (during World War II) a conscientious objector's camp were used to build the lysimeters and to carry out the early stages of research on them. Actually, construction and initial operation of the lysimeters could not have been undertaken had not the spectre of water famine been accompanied by an almost as troublesome surplus of skilled labor.

STUDIES AT TANBARK FLAT

DESCRIPTION OF THE INSTALLATION

The lysimeters are at Tanbark Flat, elevation 2,800 feet, field headquarters for the San Dimas Experimental Forest. Although sharply dissected, the immediate environs of Tanbark Flat are far less irregular and steep than the nearby, more mountainous topography (fig. 1). Chaparral unburned since 1919 (Patric and Hanes 1964) extended for several miles in all directions around Tanbark Flat. The soils and vegetation of the Experimental Forest were briefly described by Crawford (1962).

Figure 1.--Tanbark Flat and nearby mountains. The lysimeters were under construction on the cleared area near the center of this picture. Skyline elevation is about 3,500 feet. The conifers, mostly coulter pine, were planted on better sites after the native chaparral had been cleared. Photo by E. L. Hamilton, USFA.

The climate at Tanbark Flat (table 1) is typically Mediterranean with hot, dry summers following cool, more or less rainy winters. Rainfall may or may not be sufficient to recharge soil moisture. This weather pattern defines a hydrologic year beginning on October 1 with little or no soil moisture ordinarily available on chaparral-covered slopes. The master climatic station for the Experimental Forest has been within the lysimeter enclosure since 1938 and most of the climatic data used in this report were obtained there. Equipment includes the U.S. Weather Bureau class-A pan, recommended for international use as an index of evaporative demand (Anonymous 1965). The main San Dimas Experimental Forest rain gage (IF-35) is near the lysimeters. Its catch is representative of average rainfall on Tanbark Flat, varying little from gages exposed within the lysimeter enclosure. Data from gage IF-35 were used in this study and are especially useful because much additional information on rainstorms is reported (Reimann and Hamilton 1959) if needed. Actually, an 8-gage network observed throughout the 1935-36 rainy season showed virtually no variation in rainfall over the 2-acre lysimeter enclosure.

The large lysimeters were envisioned as the master group for comparing plant-water use. They are 26 contiguous concrete boxes (fig. 2), their interior surfaces coated with a waterproof and biologically inert paint that minimized reactions of concrete walls with the enclosed soil and plant roots. Troughs atop exterior concrete walls were intended to sample rain falling through the vegetative canopy. They did not function as intended and soon were disconnected from the collector tanks, after which they served to carry away rain that otherwise would drain unaccountably from wall tops into the lysimeter soil. Sloping upper and lower lysimeter surfaces provided soil drainage. Rain that did not infiltrate into the soil (i.e., surface runoff) flowed across the sloping upper surface and was conducted to collector tanks. Infiltrated rain in excess of soil water-holding capacity (i.e., seepage) drained across the sloping lysimeter bottom and was conducted to another collector tank. Rates of runoff and seepage were recorded automatically on strip charts, although collector tank catch per storm also was measured manually. A large lysimeter with all of the aforementioned appurtenances is diagrammed in figure 3.

Figure 2.--A large lysimeter before filling with soil, viewed along its long axis. The wall recesses were intended to impede water flow between concrete and soil. Note seepage opening and perforated cover plates on lysimeter bottom, and surface runoff trough on top. Photo by E. A. Colman, USFS.

Figure 3.--Diagram of a single large lysimeter.

The unconfined lysimeters were designed to show how concrete walls and bottoms influenced plant-water relations in the master group. They are pits filled with the stock soil, lying just south of the large lysimeter line and were similarly sloped on surface and bottom. Runoff from their surfaces drained from sheet-metal-bordered plots (7.5 x 14.6 feet) into collector tanks in which catch was both automatically and manually measured. There was, of course, no way to measure seepage loss from the unconfined lysimeters. The following tabulation lists further specifications for both kinds of lysimeters.

Specification	Lysimeter type	
	Large	Unconfined
Walls	6-inch concrete	Residual soil
Surface slope, top and bottom	5 percent	5 percent
Length	20 feet 9 inches	17 feet 6 inches
Width	10 feet 6 inches	17 feet 6 inches
Depth	6.0 feet	7.0 feet
Surface area	217.8 square feet	306.3 square feet
Volume	1,524 cubic feet	2,543 cubic feet
Average weight of air-dry soil	137,379 pounds	221,915 pounds
Air-dry soil density (1937) at filling	1.44	1.45
(1942) after settling	1.57	1.55

Details of the lysimeter construction, soil preparation, and filling were described at length by Colman and Hamilton (1947); only a few are mentioned here. Meticulous preparation insured that soil variability would little influence plant water-use among the lysimeters. Over 2,800 tons of soil were excavated manually from the construction site, screened free of stones larger than 3/4 inch, mixed several times, and stored in a covered bin. Mechanical analysis established that textural variation had been eliminated by this treatment. The site was roofed to prevent accidental wetting during any stage of soil processing. All of these measures were planned and closely supervised to insure a stratumless soil of uniform density. Some physical properties of the stock lysimeter soil include:

Texture - 60% sand, 25% silt, and 15% clay.

Moisture equivalent - 18% by weight.

Wilting point - 7% by weight.

Pore space - 41%.

Infiltration rate - 1 inch per hour.

Percolation rate - 0.08 inch per hour.

Soil water content was sampled occasionally by the gravimetric method from 1938 until 1954, a method too laborious and destructive of the site to encourage more frequent use. A few tensiometers were installed temporarily but not until development of fiberglass soil moisture sensing instruments, i.e. "Colman units" (Colman 1947), was soil moisture sampled regularly. These instruments were developed specifically to provide a rapid and non-destructive method to sample soil moisture in the San Dimas lysimeters. They were installed to soil depths ranging from 8 to 13 feet in the unconfined lysimeters, to 6 feet in those large lysimeters centermost in each vegetative cover. Actual placement of Colman units in the soil was 3, 6, 12, 18, 24, and 30 inches, then at 1 foot intervals downward. A few neutron probe access tubes were installed for comparative purposes in 1958 (Merriam 1959).

THE RESEARCH PROGRAM

All of the lysimeters were operated in the following stages: overfill (1937-1940), grass (1940-1946), and wildland species (1946-1960).

During the overfill stage, stock soil was piled 12 inches above the designed surface level on all lysimeters, a measure intended to compensate for settling after exposure to weather. The overfill surfaces were covered with 3 inches of new aspenwood excelsior (fig. 4) to prevent soil erosion. Average settlement on the large lysimeters was about 6 inches during the first 2 years, about 1/3 inch during the last year of overfill. Corresponding settlement was 5 and 0 inches on the unconfined lysimeters. Excelsior seemed to protect the soil from erosion during this period, but when uncovered, the lysimeter surfaces were noted to be "as hard as road pavement". All overfill above the design surface level was then removed.

Figure 4.--The excelsior cover just before removal in 1940. Note trough rain gages on top of lysimeter walls. The numbered covers could be raised to clean out surface runoff collectors. Photo by E. L. Hamilton, USFS.

The grass (*Bromus mollis*) stage provided a calibration period for the lysimeters, now with soils of established uniformity but still having the same vegetation. Large lysimeter 1 was not seeded to grass, conforming to an earlier decision that it be maintained barren of all vegetation. Succeeding years witnessed considerable change in composition of the grass cover, but no effort was made to maintain pure stands of *Bromus mollis*. Grass was most luxuriant in 1941 with the lysimeter surfaces at least 95 percent covered by plants up to 4 feet tall (fig. 5). Dry weight of grass averaged 15 pounds per large lysimeter during that year but plant density, height, and dry weight declined thereafter. The grass and litter cover was burned in February, 1946, in preparation for the final planting to woody species.

Figure 5.--The grass cover was complete but varied from year to year in vigor. Unconfined lysimeter E is in the right foreground, large lysimeters 24, 25, and 26 are behind it and extend to the left. Subsequently, border areas surrounding the lysimeters were fertilized with 150 pounds per acre of ammonium phosphate to stimulate growth of grass on them. Note deer- and rodent-proof fence surrounding the lysimeter enclosure. Photo by J. S. Horton, USFS.

The final planting to wildland species culminated a series of tests to select plants adaptable to the unique growing conditions on the large lysimeters. Early survival after planting was excellent but occasional watering was needed to insure survival as the permanent cover developed, particularly after seasons of below-normal rainfall. Weeding was needed to maintain pure stands throughout the experiment. The original planting scheme of 1 barren lysimeter and 5 replications of 5 species was modified twice (table 2). Native grasses were established in lysimeters 2 and 3 because then-current research (Croft 1950) suggested that grass used less water than did woody vegetation. Sugarbush was planted on lysimeters 14 and 16 when it became apparent that ceanothus was not thriving on them. By the mid 1950s, all lysimeters supported pure stands of wildland species, similar in size and density to natural stands. Plants on the large lysimeters, however, were somewhat smaller and less thrifty than those in and around the unconfined lysimeters (fig. 6). The planting arrangements and research facilities shown in fig. 7 were maintained until wildfire swept the installation in 1960.

Figure 6.--Coulter pines in large lysimeters 22 and 23. The trees in the border planting are much larger, an effect almost certainly caused by unrestricted root growth and possibly accentuated by fertilization. These trees were thinned to 5 per lysimeter shortly after this picture was taken. Shrub in left foreground is scrub oak. Photo by J. H. Patric, USFS.

Figure 7.--Plan of lysimeter enclosure at Tanbark Flat.

Plant growth was observed keenly and recorded often. Grass, chamise, sugar bush, and especially buckwheat grew well in the large lysimeters. Subject to an unknown disease, ceanothus was replaced in 2 lysimeters. Scrub oak tended to develop gangly shoots in wet weather, then to die back in dry seasons. It was pruned in 1951, a vain attempt to grow a more uniform stand. All of these species were planted thickly, then thinned to suitable density after surviving plants were well established.

Coulter pine illustrated especially well the difficulty of growing large woody plants in relatively small containers. Planted 1 per square foot, they were thinned heavily in 1947 and 1948, then in 1951 to 1 tree per 16 square feet. In 1956, these trees were thinned to 8 per lysimeter, then to 5 in 1959, with ultimate plans for 1 tree per lysimeter. An aphid infestation was noted in 1956. A memo of May 1958 recorded that a European fungus (Lophodermium spp.) had caused needle cast. Another memo (June 1958) attributed needle deformity and yellowing to heat damage and moisture stress. The net effect of these and other conditions was markedly reduced growth of coulter pine on the large lysimeters (Patric 1961b).

Plant height, crown density, litter cover, and soil depth permeated by roots greatly influence rainfall disposition under vegetation. Many such measurements were recorded, the most complete concerning observations of 1951 (table 3). Note that plant growth was most vigorous in all respects on the unconfined lysimeters. Ten years after planting, all of the lysimeters had complete litter covers, but it was thickest under taller and heavier-crowned vegetation growing on the unconfined lysimeters. Estimates of crown density (based on oblique photographs) varied from 10 to 45 percent on large lysimeters, but a range from 20 to 30 percent was most common during the final years of observation.

Phenology notes were taken more or less routinely during soil moisture sampling. The most complete of these (Appendix table 7) described growth habits of the lysimeter species during 1959, the last year before the wildfire.

The record concerning root growth contains fewer measurements. It was known from excavations during planting experiments that all species grown on the lysimeters would root at least to 30 inches within 2 years. A memo of October 1947 notes "fat and fresh-looking" scrub oak roots observed from the tunnel in a seepage chamber at the bottom of a large lysimeter. By late summer 1947, soil in all lysimeters containing buckwheat, chamise, and ceanothus had dried throughout, below the wilting point as determined with sunflowers. Apparently, these soils were fully permeated by roots; certainly, all of the available soil moisture in the large lysimeter was accessible to plants growing thereon. A memo of August 1949 reports live roots in soil samples taken at depths of 10 to 12 feet in the unconfined lysimeters. By 1955, grass roots were noted in seepage chambers beneath lysimeters 2 and 3. It seems reasonable to believe that roots completely permeated soils in all lysimeters within 3 or 4 years after planting.

These and other noteworthy events that shaped lysimeter research at the San Dimas Experimental Forest are listed in Table 4.

The possibility that plant water-use was modified by the soil-concrete interface on large lysimeter bottoms haunted San Dimas personnel throughout the experiment. A memo of December 1939 noted that 3 inches more water was retained in the large lysimeters than in equivalent soil depth in the unconfined lysimeters. Subsequent tests based on gravimetric sampling (memo of June 1942) and on tensiometers (memo of July 1943) left no doubt that soil at the bottoms of large lysimeters often was saturated to depths up to 3 feet during wet weather. At the same time, soil at equivalent depths in unconfined lysimeters showed negative pressure potentials and no evidence of saturation. A method ultimately was developed to nullify the soil-concrete interface (Colman 1946) but the device never was used on more than a demonstration basis. Moisture sampling with soils at the maximum wetness observed (April 8, 1958) showed that 6 feet of large lysimeter soil contained about 2-1/2 inches more water than the same depth of soil in unconfined lysimeters (Appendix page 110).

A lesser difficulty concerned spurious seepage or "side-wall flow", surface runoff descending between lysimeter walls and the enclosed soil, finally draining into the seepage collection tanks. Unquestionably, the lysimeter soils shrank sufficiently during summer drying to pull away from the walls, thereby permitting free descent of early winter rains until the wetting soil swelled sufficiently to close off such descent. A memo of June 1940 describes "a veritable cascade of water, descending from the top of the seepage compartment in lysimeter 10 which had been suspected of such action". Efforts to seal soil cracks and other avenues of sidewall flow never were wholly successful. Bookkeeping methods finally were devised to account for sidewall flow and thus to maintain accurate partitions of rainfall into surface runoff and seepage. In later years of the experiment, sidewall flow was recognized and recorded as surface runoff during all fall rains, long before soil in large lysimeters had absorbed enough water to begin true seepage.

Although it interrupts the narrative, some recent observations concerning the lysimeters seem appropriate at this point. Little is published concerning actual damage by the fire of 1960, either to installations or to vegetation. But regardless of the damage, research personnel were urgently needed for rehabilitation studies elsewhere, and the lysimeters were virtually abandoned. I revisited Tanbark Flat in 1972 and noted the following conditions. Some chamise, sugarbush, ceanothus, and scrub oak but no coulter pine remained on the large lysimeters. On these, buckwheat formed a conspicuous understory but it completely occupied all other large lysimeters. Despite weeds, neglect, and some evidence of fire damage, woody vegetation on unconfined lysimeters and in surrounding border planting looked thrifty and remained about as planted in nearly pure stands. It was conspicuously larger than vegetation on large lysimeters.

RESULTS

The installations and research program described inevitably produced a flood of data. The effort needed to collect and record observations effectively precluded their analysis; time, personnel, and techniques seldom were available in combinations needed to keep data processing abreast of collection. Thus, even long after the fire, certain decisions were needed, in effect, to reduce this volume of data to manageable size. (1) All strip chart records were rejected out of hand, not solely by reason of their bulk, but also because of long standing suspicion that work with them was pointless, that rainfall diverted to runoff on lysimeters greatly exceeded such diversion on less artificial surfaces. (2) Results would be based on annual rather than shorter-term analysis. Preliminary work had shown that daily, weekly, sometimes even monthly variation among lysimeters as well as species produced such a welter of conflicting details that overall directions could not be determined.

(3) Annual data would be averaged for all large lysimeters growing like vegetation, preliminary testing having shown no consistent differences among their performances. Lacking these data reduction decisions, the lysimeter results would have proven both too inconclusive and too massive for publication. However, the complete lysimeter record is stored in a federal records center, available for more detailed analysis by qualified scientists through the Pacific Southwest Forest and Range Experiment Station.

RAINFALL DISPOSITION BASED ON ANNUAL WATER BALANCE (1937-59).

Large Lysimeters

All hydrologic data continuously available (rainfall per storm, runoff per lysimeter during storms, and seepage per lysimeter after storms) were processed at the University of Massachusetts computer center. Printout showed, by hydrologic years, the average water balance per storm for all lysimeters having like vegetation. The computer program applied the Conservation of Mass principle to each storm, attributing all unmeasured loss of precipitation to evaporation as:

$$\text{Evaporative loss} = \text{Precipitation} - (\text{surface runoff} + \text{seepage}) \tag{1}$$

Interception losses were estimated per storm using equations shown in Appendix table 8. The residual of precipitation not accountable as surface runoff, seepage, or interception loss was thus attributed to soil moisture loss, an estimate of annual transpiration by lysimeter vegetation. These data are summarized by hydrologic years in Appendix table 9 and most of the following annual results are drawn from entries in that summary.

Infiltration (annual precipitation - surface runoff - interception loss) rates did not change during the 3 years excelsior covered the large lysimeters but, as shown in the following tabulation, it increased markedly under grass:

Hyd. Year	Infiltration (inches)	Percent of precipitation
1940-41	7.65	16
1941-42	12.21	73
1942-43	17.40	38
1943-44	15.77	47
1944-45	14.73	50
1945-46	18.77	70

There was no other time-trend of infiltration from 1946 to 1959. Although the differential was by no means constant, about 10 percent more of the annual rainfall infiltrated into unconfined lysimeter soils. But year-to-year variation among infiltration rates, on bare as well as vegetated surfaces, clearly was a function of amount and intensity of rainfall. For any given year after 1945, infiltration was remarkably consistent among vegetated lysimeters, suggesting that factors other than plant cover--probably the slow percolation rate--controlled the infiltration process.

Surface runoff clearly reflected these infiltration changes. After the excelsior-cover period, runoff was substantially reduced by vegetation, finally varying linearly with precipitation regardless of species (fig. 8). Again, the grass cover period is of interest. In 1940-41, the first year under grass, average runoff from the large lysimeters almost coincided with runoff from the bare one. This behavior suggests that soil structure, probably little modified under excelsior, had not changed much the first year under grass. But during the next 4 years, runoff from the grass-covered lysimeters gradually changed from that resembling bare soil to that observed after 1946 under all vegetative covers. Yearly runoff under grass is labelled in figure 8 to facilitate following this slow change. Over this period of record, runoff averaged 68 percent of annual precipitation on the bare soil lysimeter, only 27 percent after plants were 4 or more years old on large lysimeters. Somewhat higher proportions of runoff under juvenile vegetation presumably reflected structureless soil and lack of an effective litter cover on its surface.

Figure 8.--Vegetation effects on annual runoff from large lysimeters.

Seepage occurred after water absorbed into the soil exceeded its water-holding capacity and the resulting pore saturation overcame the soil-concrete interface along the lysimeter bottoms. Although 1937-38 was a very wet year (48.13 inches of rain), seepage was erratic from the newly filled lysimeters and these data are not reported. Variable rates of soil wetting, soil cracks, settling, and sidewall flow caused this irregular performance. Sidewall flow, incidently, was more factually reported as surface runoff after 1937. Seepage, continuous under excelsior throughout 1938-39 and 1939-40, did not vary significantly (.05) among the lysimeters. Even though precipitation was heavy in 1940-41, high runoff rates--in addition to evapotranspiration by newly planted grass--resulted in negligible seepage from all large lysimeters.

A memo of July 1940 reports that barometric pressure caused fluctuating seepage rates from the large lysimeters. A sensitive recording mechanism mounted on the collector tank for lysimeter 23 showed least seepage to be associated with high pressure at 11 A.M. and P.M., most seepage to be associated with low pressure at 3 A.M. and P.M. Years later, fluctuating outflow from draining soil in North Carolina was similarly correlated to barometric pressure (Hewlett and Hibbert 1963). Apparently, this discovery was not pursued further at San Dimas.

It is noteworthy that 1940 was the only year when most water seeped from lysimeter 1. Newly bared, surface runoff from it was high but there was no vegetative cover to withdraw abundant water previously absorbed under excelsior, so some of the little rain that did infiltrate in 1940 seeped out slowly thereafter. The records suggest that minor seepage from lysimeter 1 was real after heavy rains in 1943 and 1957 but that some form of leakage caused "seepage" in 1945 when only moderate (26.85 inches) rainfall occurred. At any rate, seepage from lysimeter 1 was negligible from the first year after soil-baring, grass-covered lysimeters seeped annually after establishing characteristic infiltration rates, and lysimeters covered with woody vegetation produced modest seepage only after more than 40 inches of rainfall, far more than average for Tanbark Flat.

Water absorbed annually into lysimeter soil during rainy seasons was lost during subsequent dry seasons, slowly by direct evaporation from bare soil surfaces or rapidly by transpiration from the wetted-soil depth (fig. 9). Although evaporation from the bare lysimeter varied significantly (.05 level) with annual precipitation, frequency of rewetting probably influenced the evaporative rate more than did absolute amounts of water contained in the soil (Milthorpe 1960). Soil moisture used by grass was uninfluenced by annual precipitation as experienced from 1940 to 1959. This fact, in addition to annual seepage yield, suggests that precipitation always replenished soil moisture beyond the water needs of grass for transpiration and other vital processes. In sharp contrast, lack of available soil water always limited evaporative losses from large lysimeters covered with woody vegetation. A semi-logarithmic relation of soil moisture loss to rainfall best described this limitation. Annual soil moisture losses from the large lysimeters are contrasted under extremes of precipitation in the following tabulation:

Vegetative cover	Inches of soil moisture lost per year		
	driest	average	wettest
Bare	6.47	8.42	10.61
Grass	10.30	12.94	12.20
Woody species	8.51	13.82	20.36

Figure 9.--Soil moisture loss from large lysimeters, bare and vegetated.

Unconfined Lysimeters

Time trends of hydrologic performance on the unconfined lysimeters followed those set in the large lysimeters. Annual infiltration increased with time under grass, but was unaffected under woody vegetation. As previously noted, annual infiltration was about 10 percent higher on these unconfined soils, with surface runoff correspondingly reduced. Runoff averaged 22 percent of annual rainfall after woody vegetation was 4 or more years old. Analysis of variance showed no effect of woody vegetation on runoff among the unconfined lysimeters but average annual runoff was 0.28 to 2.35 inches less than on large lysimeters, with the mean decrease (1.11 inches) significant at the .05 level of probability.

Surface runoff from all grass-covered lysimeters exceeded about 100-fold (table 5) that of natural chapparal slopes with sandier soils. Unfortunately, additional data concerning runoff from natural slopes were not published to permit runoff comparisons after wildland species were planted on the lysimeters. It is unlikely that disproportionate runoff was caused by grass because that did not happen on nearby steeper plots at Tanbark Flat: "Since establishment of a complete grass cover, there has been no appreciable amount of runoff or water-carried erosion from the plots" (Rowe and Reimann 1961). Two other pieces of information further evidence excessive surface runoff on all of the San Dimas lysimeters. The plots referred to in table 5 range in slope from 35 to 50 percent (Sinclair et al. 1958), about 10 times steeper than lysimeter surfaces. Furthermore, the Fern Canyon plots are steepest and rainiest of all and were burned over in a wildfire of 1938. Runoff from them, considered well above normal (Rowe et al. 1954), was far less than surface runoff even from the unconfined lysimeters.

Tension-water content relationships (table 6) suggest some approximate upper and lower limits of water storage in lysimeter soils. Seepage always started when water content of large lysimeters exceeded 22 inches or about 0.15 bar tension, thereby setting an upper limit of storage capacity. Assuming that tension 0.15 bar also limited storage in the unconfined lysimeters, then water content in 10 feet of soil was about 36 inches. The records suggest that only during 1957-58 did unconfined lysimeters attain this wetness; full depth wetting being, of course, more common in shallower soils of the large lysimeters. The preceding water-content maxima are based on the assumption of uniform soil wetting, so must be used cautiously because non-uniform wetting is the rule.

At the opposite end of the wetness scale, water content at 15 bars--the conventional "wilting point"--was an annually observed phenomenon of great physiological significance. Plant water-use became very slow or ceased at this tension, and water content of both large and unconfined lysimeters always fell close to this non-use level (Appendix table 10). Thus, both kinds of lysimeters ended most hydrologic years with minimum water available for plant use and with maximum rainfall storage capacity. Bare soil and grass, however, never dried the large lysimeters to this extent.

The few data available suggest almost no change over time in soil physical properties that determine water relations. Undisturbed samples removed during 1973 from the 0 - 3 and 4 - 7 inch levels in large lysimeter 6 had retained the average bulk density (1.55) observed 25 years earlier. Soil water-tension relationships also were unchanged.

Differential soil drying may express plant drought resistance as, for example, was shown when five herbaceous species dried a Mumford soil to tensions ranging from 5 to 40 bars (Sykes and Loomis 1967). These authors felt that a permanent wilting point of 15 atmospheres was unjustified for all plants and soils. The lysimeter results (Appendix Table 10) bear out their contention and provide the following scale of drought resistance. Buckwheat and chamise reduced soil moisture to lowest levels (6.2 inches) in the large lysimeters and seemed most drought resistant. Sugarbush, ceanothus, and scrub oak left about 1 inch more soil moisture at the end of most growing seasons. Coulter pine ordinarily dried large lysimeter soils least and presumably was least drought resistant. Analysis of variance showed that these differences were significant at the .05 level of probability. These relationships were, of course, less clear in the unconfined lysimeters where plant water-use was not restricted to a definable volume of soil.

RAINFALL DISPOSITION BASED ON SOIL MOISTURE MEASUREMENT (1952-59).

Large Lysimeters

A key question must be answered before considering soil moisture loss derived from Colman units: "Did these instruments provide reliable soil water content data?" An answer to this question is essential because some uncertainty has been associated with their use (Horton 1955). Fortunately, several checks are possible.

Because the Conservation of Mass law applies, the sum of all measured water losses from the large lysimeters must equal precipitation. Following is the mean annual water balance for lysimeters 1,3,5,9,14,15, 19, and 24 during years when soil moisture was measured with Colman units:

Mean annual precipitation	23.25 inches
Surface runoff	6.85 inches
Seepage	0.81 inches
Evaporative losses (soil moisture and interception)	16.10 inches
Sum	23.76 inches

Agreement on the order of 1/2 inch between measured precipitation and the water balance is gratifyingly close. There was, of course, measurement error associated with all sampled components of the water balance. Seepage and surface runoff were measured volumetrically, so can be disregarded from consideration of sampling accuracy. Precipitation samples almost always reflect a wind-caused negative bias (Corbett 1967), McGuinness (1966) having demonstrated 6 percent more catch on weighing lysimeters than in nearby standard raingages. Raingage IF-35 at Tanbark Flat is in a forest opening so its negative bias probably was less than that reported by McGuinness, whose gages were fully exposed to wind in open fields. The estimation of rainfall interception by chaparral and grass is beset with uncertainty (Corbett and Crouse 1968), but amounts of water involved were relatively small.

Although the accuracy of soil moisture sampling by Colman units is most open to question, a few checks on them are possible. (a) Estimates of soil moisture loss based on Colman unit data sometimes exceeded those based on water balance but the differences tested statistically nonsignificant (at .05). (b) Soil water content estimates based on Colman units and gravimetric samples did not differ consistently (Appendix table 11). (c) Merriam (1959) found close agreement among estimates of lysimeter soil water content based on gravimetric, neutron probe, and Colman unit sampling. The evidence suggests a high order of accuracy among all sampling techniques, with underestimated rainfall the most probable explanation of nonagreement between the precipitation and the long-term water balance. Thus, annual soil moisture losses based on Colman unit sampling are considered reasonably accurate, probably within ± 5 percent of true values.

This accuracy evaluation does not pertain to short-term estimates of soil moisture loss or gain; Colman units sometimes did evidence anomalous soil moisture changes between readings. They seemed most erratic when early winter rains began to rewet soils after summer droughts, on occasion evidencing soil moisture gains greater than, less than, or equal to rainfall. Discussion with J. Y. Parlange (Department of Engineering and Applied Science, Yale University) established that such behavior is hardly cause for alarm; indeed, it must be expected. Not only is rain distributed unevenly beneath vegetation, but infiltrated water probably followed "preferred" paths along roots, soil cracks, and animal holes. Even in soils not thus predisposed to uneven wetting, "fingers" possibly would form during wetting anyway (Hill and Parlange 1972). The "stacked" arrangement of Colman units probably accentuated this more-apparent-than-real problem, providing single columnar samples as wetting advanced by different and uneven fronts during each storm. I was convinced, despite all efforts to minimize them, that soil and plant idiosyncracies caused more variation among short-term soil water content data than did malfunctioning Colman units. Obviously, this impression cannot be verified.

Since electrical resistance in Colman units indicates soil moisture tension (Colman and Hendrix 1949), two useful albeit imprecise quantities established upper and lower limits of water availability to plants:

1. "Field capacity" was assumed when moisture index (corrected moisture dial readings as per Horton, 1955) exceeded 140. These high moisture indexes occurred only after heavy rain, were sustained by continuing rain, and lowered a few days after rain stopped. Seepage always occurred when the entire profile in large lysimeters exceeded moisture index 140. The assumption of field capacity, with water freely available to plants, seemed justified because macropores had to drain to produce these effects.

2. "Wilting point" was assumed when the moisture index reached some annually recurring low level after prolonged soil drying. Plant growth had ceased at these times and general appearances of extreme dryness left little doubt that soil water was minimally available to plants. Low moisture index persisted at any level in the soil until percolating rain finally sank to that level.

Figure 10 shows where and when these conditions of soil moisture availability occurred during the final 4 years of record collection on the large lysimeters. Although the bare surface of lysimeter 1 dried rapidly and completely, soils below 3 inches never dried to wilting point and soils below 18 inches remained at or near field capacity. Heavy surface runoff usually prevented the bare soil from wetting sufficiently to start seepage. Even the upper foot of soil in lysimeter 3 (grass) seldom dried to wilting point, and soil below 3 feet always remained near field capacity. With relatively slight surface runoff, the rainfall of driest years was sufficient to rewet the grass soils to field capacity and to restart seepage. Soil moisture storage and use under woody species differed only in detail. Drying full-depth to wilting point occurred annually (Appendix table 10) except when heavy rain in 1957-58 forestalled extreme water loss during the subsequent drying season; after so heavy a rain, even the bare soil dried less than usual. Seepage occurred under woody vegetation in 1957-58 when rains were adequate to fully recharge the entire large lysimeter soil profiles.

Figure 10.--Depth, duration, and severity of soil drying in the San Dimas large lysimeters. Darkest shading indicates soil moisture near field capacity, no shading indicates soil moisture near wilting point, and light shading an unspecified degree of water availability to plants between those extremes.

Zinke (1959) contrasted soil moisture regimes in bare and pine-covered lysimeters, using a more sophisticated application of this method.

Rainfall was below normal throughout the period of soil moisture measurement, except in 1957-58. Evaporative losses differed little during the dry years, so these data were averaged for the bare, grass, and woody-vegetated lysimeters. Monthly and annual evaporative losses for both wet and dry years may be compared in Appendix table 12. Although plant cover exerted some control over monthly rates of soil drying, precipitation governed the total amount of water available for evaporation. The ratios of actual to potential evaporative loss (fig. 11) provide additional insight into influence of vegetation on water loss from lysimeters.

Figure 11.--Ratios of actual to potential evaporative losses for wet and dry years. For all lysimeters containing Colman units (large - 5, 9, 15, 19, and 24; unconfined - A, B, C, D, and E).

Qashu (1969) applied these same soil moisture data somewhat differently, concluding that water use did not differ among the species tested and was controlled by available soil moisture.

Before going on, the anomaly of soil moisture loss considerably exceeding pan evaporation must be dealt with, albeit uncertainly so many years after the fact. Uneven soil wetting played a part already considered. Uneven soil drying is at least as possible; for example, roots clustered around a Colman unit could have indicated drying far in excess of that which actually took place throughout the sampled soil stratum. It is noteworthy that this anomaly always occurred in the cool, wet winter months. Perhaps conditions actually prevailed in which radiation, albedo, heat storage, plant physiology, and freely available water combined to cause short-period evapotranspiration exceeding pan evaporation. Other explanations, including human and instrumental error, are possible but fruitless. It is reassuring that use of annual soil moisture data seemed to integrate all such error, evidencing long-term evaporative losses quite in line with the computed water balance. Nevertheless, short-term evaporative losses from the San Dimas lysimeters must be interpreted cautiously because of uncertainties unavoidably associated with them.

Wet year evapotranspiration considerably exceeded that of dry years (fig. 11). Evapotranspiration at near-potential rates[2/] was possible during any month

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[2/] An index of potential evapotranspiration was obtained by multiplying the appropriate coefficient (0.7) for Southern California by Class A pan evaporation (Kohler et al. 1959).

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from November until April because atmospheric demand for water was low and soil moisture was freely available after heavy rains. For an extreme example, over 10 inches of rain fell in February 1958, with pan evaporation only 1.62 inches. Ordinarily, interception was the major evaporative loss of early winter but transpiration caused much greater losses thereafter. The effect of wetting frequency on evaporation from bare soil is apparent, with losses close to potential rates restricted entirely to the wettest of the rainy season months. Greatest evaporative loss from grass also tended to occur in winter. Pine used most water in late winter, chaparral species most in early summer, a behavior of wildland plants more apparent in Appendix table 12 than in figure 11. No chaparral plant used soil moisture at rates consistently different from any other.

All of these woody species are evergreen, so physiological reasons for contrasting schedules of water use are not apparent.

Unconfined Lysimeters

The soil moisture record for the unconfined lysimeters is incomplete for 1957-58. A troublesome omission, this very wet year afforded an only opportunity to examine water use by free-to-grow woody species abundantly supplied with water. Even though regularly observed electrical resistance readings had been recorded and processed through the "moisture index" stage, inches of water represented by that moisture index had not been compiled, and plant-water use could not be determined. Apparently, these Colman units had not been calibrated for soils of this unprecedented wetness. Soil moisture data are complete for the dry years preceding 1957-58 (Appendix table 13) but the following water balance suggests some inaccuracy:

Average annual precipitation (1952-1957)-------20.06 inches

Losses	Chaparral	Pine
Surface runoff	2.04 inches	5.48 inches
Evapotranspiration and deep seepage	19.98 inches	13.53 inches
	22.02 inches	19.01 inches

Surface runoff during 1957-58 was exceptionally high (25.56 inches) on unconfined lysimeter D. Reasons for exceptional runoff are not known, but it served to keep soil moisture within the range of previously experienced wetness. This circumstance suggested an improvised method to supply the missing and wanted soil moisture data. Most of the 1957-58 moisture index values could be found in the pre-1957 soil moisture record, matched with the equivalent inches-of-water. This inches-of-water figure from the pre-1957 record was entered under the appropriate moisture index in the 1957-58 record. A few such sought-for pairings were not in the older record; here, inches-of-water were approximated by extrapolation from the available pairings closest to 1957-58 moisture index. By these methods, a reasonably credible record of soil moisture use was developed for scrub oak. It was not possible, by these or other methods tried, to improvise a similarly credible record of soil moisture use by plants on the other unconfined lysimeters.

Figure 12 compares soil moisture regimes of large lysimeter 19 and unconfined lysimeter D. Both "wilting point" and "field capacity" have been defined previously and the methods used to determine amounts of soil moisture loss have been described. With both lysimeters growing scrub oak, this overall similarity of plant-water use was not unexpected. Greatest fluctuation of water content always occurred in uppermost soils; only the uppermost soils wetted to field capacity every year. Some soil wetting always occurred to full lysimeter depth, regardless of rainfall amounts, the "wetting front" described by Colman and Bodman (1944) being not at all prerequisite to partial wetting of deep soil. Measurable water always was lost from all soil depths. Both lysimeters completely wetted to full soil depth during the rainy year (1957-58). Drying at any depth did not begin until considerable water had previously been drawn from the immediately overlying soil.

Figure 12.--Three years of water loss from deep and shallow lysimeter soils containing scrub oak. Shading indicates energy status of soil moisture as in Figure 10. Soil depths are 1 foot intervals; soil depth 0 for example, represents soil from 0 to 1 foot deep.

Several effects of lysimeter bottoms became apparent after soils wet to full depth in 1957-58. Note a small soil moisture loss (0.30 inch) at 11 to 13 feet in the unconfined lysimeter during April and May. Although rain ceased early in April, water was abundant and freely used from the uppermost 6 feet of soil. There was no evidence of plant water use from the 6 to 10 foot soil depth, so this loss of 0.30 inch is thought to be deep seepage. So small a quantity of deep seepage probably sank only a few inches beneath the lowest Colman unit. With heavy water use measured at 13 feet in August, it is assumed that this deep seepage also was taken up by plant roots and that all water infiltrated into unconfined lysimeter D was lost later to transpiration. With considerably more rain (9 to 16 inches) infiltrating into the other unconfined lysimeters, perhaps some of the infiltrated rain did sink beneath the reach of plant roots there.

Note that surface soil in unconfined lysimeter D contained available water throughout 1958. With soil moisture still abundant at 8 to 13 feet by late s mmer, soils at 0 to 6 feet had not dried as usual to wilting point because water always had been available to scrub oak plants thereon without need to develop maximum suction anywhere in the root system. Water was carried to the plants by two interdependent mechanisms: (a) greatest amounts were carried most rapidly in roots but (b) a lesser and slower upward flow through soil as vapor must have occurred when tension gradients developed in response to drying from the surface downward. Concrete bottoms in large lysimeters eliminated any possibility of either kind of upward movement from soils below 6 feet. Lysimeter bottoms actually had robbed plants of most of this water, months before it was needed. Water diverted to seepage collector tanks during heavy spring rains would have, if not stopped by lysimeter bottoms, percolated to soil depths greater than 6 feet. There it would have been stored until scarcity in shallower soils drew it upward by either of the mechanisms described.

Figure 12 leaves the impression that large lysimeter results are merely a truncated version of events in unconfined lysimeters, an impression strengthened by Figure 13. Mean water loss from large lysimeters 5, 9, 15, 19, and 24 was based on regularly sampled soil moisture content and on seepage measurements. Mean water loss from unconfined lysimeters A - E is based on my best estimate of soil moisture loss, including deep drainage. For whatever the comparison is worth, water losses April to June were the same from both kinds of lysimeters. Seepage from large lysimeters lasted into June; presumably deep drainage persisted almost as long from the upper 6 feet of soil in the unconfined lysimeters. The nearness of these lines through June suggests identical soil moisture losses. After July 1, soil moisture losses to 6 feet are reckoned accurately, insofar as the sampling method is accurate, because soils had dried by then to previously experienced water content.

Note that large lysimeters lost water in August much more rapidly than did the upper 6 feet of soil in the unconfined lysimeters. This greater August water loss was drawn almost entirely from the soil-concrete interface at 4 to 6 feet in the large lysimeters. But water loss at 0 to 6 feet from unconfined lysimeters was augmented by increased loss from deeper strata. Indicated use to 13 feet (Fig. 13) must be regarded as a mere minimum estimate: the Colman units provided no way to calculate soil moisture loss from the entire rooting depth of the woody plants.

Figure 13.--Cumulative water use from lysimeters with fully wetted soils. From last rain (April 7) to end of 1957-58 hydrologic year. Each line depicts mean soil moisture loss from five lysimeters.

Lacking measurements of seepage and soil moisture, we have no way to know how much water was used by vegetation on the unconfined lysimeters in 1957-58. We can, however, deduct from rainfall all measurable water losses (surface runoff and interception) to arrive at the following--probably realistic--estimate of potentially available soil moisture. Presumably, all of it was lost to evapotranspiration.

Unconfined lysimeter	Infiltrated rain (inches)
A (buckwheat)	29.98
B (chamise)	33.43
C (ceanothus)	26.32
D (scrub oak)	17.48
E (coulter pine)	30.22

At least 30 inches of water could have been transpired by buckwheat, chamise, and pine growing on the unconfined lysimeters. With evaporative demand (0.7 x Class A pan evaporation) about 34 inches from April through December 1958, it is conceivable that some of these plants transpired at close to potential rates throughout 1957-58. Failure of soil in lysimeter D to dry to wilting point adds weight to this argument because soils in other unconfined lysimeters were even wetter and correspondingly better able to supply water for transpiration at atmospheric demand. How much of this evaporated water was drawn from soils beneath the maximum sampling depth (13 feet) cannot be known. I surmise that water was there and know that chamise and scrub oak roots extended deep enough to reach it (Hellmers et al. 1955).

Figure 14 is a more or less conceptual version of vegetation effects on drying of lysimeter soils initially wetted to full water-holding capacity. The end points and flexures for all large lysimeter curves and for the unconfined lysimeter curve for wildland vegetation are near actually determined values. None of the unconfined lysimeters was bare or grass-covered during the period of soil moisture measurement, so these curves are hypothetical. I assumed that bare and grass-covered soil would dry as rapidly and to the same extent in both kinds of lysimeters because total soil depth is well beneath levels from which soil moisture is drawn under these covers. All of these curves probably depict rather accurately the drying of fully wetted soil at Tanbark Flat. The curve for wildland vegetation is steeper and shorter for large lysimeters, plants thereon being restricted to contained soil moisture. Lysimeter walls are seen to impose rigid limits on amounts of soil moisture available for transpiration but as having negligible effects on its rate of loss until perhaps two-thirds of the available water is used.

Figure 14.--Influence of vegetative cover on soil moisture losses from large (solid line) and unconfined lysimeters (dashed line).

DISCUSSION

The fire that terminated lysimeter research at the San Dimas Experimental Forest (Figure 15) provided a solution of sorts to a problem that would have demanded intense soul searching in the conventional administration of forest hydrology research. Were the lysimeters paying off in terms of applicable research results? Circumspectly but insistently, this question was posed in the late 1950's. The lysimeters represented, in terms of forestry research budgeting, a continuing and heavy drain on talent, time, energy, and public funds. But after 20 years of dedicated effort, the list of published findings was unimpressive.

Figure 15.--The San Dimas lysimeters after the wildfire of July 1960. Large lysimeters 4, 5, and 6 (left foreground) and unconfined lysimeter A (right foreground) had been burned clean of buckwheat. The leafless, blackened stems behind the kneeling observer are chamise. Firemen were able to save coulter pine in unconfined lysimeter E (right center background) and the climatic station (extreme right). Photo by J. E. Linder, U.S.F.S.

The major finding, that water use by bare soil was less than that used by grass, which was less than that used by woody species, merely confirmed Zon's (1927) venerable conclusion to that effect, drawn from even earlier European research. Nevertheless, these facts were sufficiently important to merit testing on a larger scale. Subsequently, it was confirmed that conversion of chaparral to grass materially decreased soil moisture losses (Merriam 1961 ; Rowe and Reimann 1961) and increased streamflow (Crouse 1961; Rowe 1963), i.e. water available for human use. But in the steep mountains of the San Dimas Experimental Forest, such increases were achieved at the intolerable risk of slope instability (Corbett and Rice 1966; Orme and Bailey 1971). Other conversion of brush to grass, primarily for fire control on modest slopes, was additionally justified as a water-producing measure (Bentley 1961). But bitter experience with fire-caused floods and severe soil erosion (Sinclair et al. 1954) rendered unthinkable the deliberate conversion of any brushland to bare soil.

Another finding bore directly on the original lysimeter research objectives; although woody species ordinarily transpired all soil moisture available to them, availability levels differed among species. Buckwheat and chamise, for example, could deplete soil moisture to lower levels than scrub oak and coulter pine. But this finding has little relevance to practical watershed management. As pointed out by Sykes and Loomis (1967), the wilting point does vary with species, some are able to use water unavailable to others, and this ability may prove vital to their survival in drought situations. Probably buckwheat's ability to so survive contributed to its post-fire takeover of many large lysimeters. But does extra water available to drought resistant plants have any real potential to relieve water scarcity in southern California? I think not, the small amount of water to be gained by eliminating a species such as buckwheat being far less costly when obtained by other means. But even if buckwheat erradication could be justified in terms of economical gains in water yield, important ecological questions would arise. What plant would replace buckwheat? Nothing would be gained by chamise replacement and the more modest water users (except grass) likely could not thrive on buckwheat sites.

Could water quality be maintained on catchments so managed? Probably efforts to produce more streamflow by eliminating one or more of the woody species would prove fruitless, on economic as well as ecological grounds.

Except for development of the Colman unit, actually a sort of by-product, there had been no especially useful outcome of lysimeter research that might conceivably have application in alleviating southern California's water shortage. But despite a dearth of fanfare, the hydrologic results achieved had been observed repeatedly (Appendix Table 14), under conditions of rigid experimental control. This is an important value, sometimes overlooked in evaluating the results of watershed management research. The sheer time span over which these results were observed added much to their strength. Many results of soil-plant water research have been inadequately replicated over time and space. In studies of forest-water relations, the San Dimas lysimeter research may stand alone in this important respect.

This matter of payoff will never be dealt with to everyone's satisfaction. But the fire provided a ready answer, regardless of its aptness, concerning equally sticky questions as to useful directions for future lysimeter research. It stopped. Now, many miles and several years removed, other research values have come into focus.

The major additional value is that lysimeters can better be judged as to their effectiveness for forest hydrology research. Their advantages are well known (Rutter 1968) and their greatest advantage has been mentioned, that water relations of plants can be compared in them under conditions of minimum environmental variation. Following are some limitations discovered in the San Dimas lysimeters as sites for studying water relations for wildland species in southern California:

1. Low infiltration rates enormously increased the diversion of rain to surface runoff, thereby reducing soil moisture available for plant use. Although reasons for these low infiltration rates are not wholly clear, comparison of soil properties provides a few clues. Subsoil percolation rates were much lower in lysimeter soil (0.08 inches per hour) than in nearby natural subsoil (0.99 inches per hour).[3/]

[3/] Personal communication, Dr. Raymond Rice, Glendora, California.

Lysimeter soil contains about twice as much clay as soils on the runoff plots, and it swells considerably with wetting.[4/] However, the lysimeter soil was not

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[4/] Personal communication, Dr. Leonard De Bano, Glendora, California.

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atypically compact, differing little in bulk density from soils observed elsewhere on the Experimental Forest (Rowe and Colman 1951). Slightly reduced infiltration into large lysimeters may reflect presence of walls which,

coupled with greater biological activity in the unconfined lysimeters, probably influenced air displacement in soil during heavy rains. Infiltration is hindered when air is not free to escape as it is displaced by water in a wetting soil (Philip 1969).

Hindered infiltration into the bare soil of lysimeter 1 was described in a memo of January 1956; during a moderate rain, bubbles formed continuously in a water film covering the soil surface. Had it occurred on litter-covered lysimeters, this bubbling could not have been observed. In fact, it was unlikely to be noticed anywhere during the turmoil of heavy rain. The important response was that all soil moisture losses (seepage, direct evaporation, and transpiration) were minimized by extraordinarily high rates of surface runoff.

2. The concrete walls unquestionably curtailed water use by woody plants in large lysimeters. Normal water use was impossible in dry weather because roots were restricted to water stored within the walls. On the other hand, plants outside the lysimeters were prevented from competing for water stored therein. The advantage of non-competition, however, seems to have been far outweighed by the disadvantages of root confinement. In addition, vapor flow along soil moisture tension gradients also stopped at concrete walls. Probably no restrictive effect of walls curtailed water use by grass because ample moisture always was available beneath it at soil depths greater than 3 feet.

3. The normal gravitational flow of infiltrated rain was altered, but only after large lysimeter soils were wetted to full water-retaining capacity. Then, most water in excess of capacity drained away as seepage and was lost to plant use. The remainder accumulated at the soil-concrete interface on lysimeter bottoms. In effect, this remaining interface water was "ponded", readily available for plant use although it may have interfered with root functioning. In the normal soil-plant system, this water--not "ponded"--was distributed more diffusely in the soil but was hardly less available to the chaparral species. This interface effect, long a major concern in lysimetry (Kitteredge 1940), is seen as a factor of negligible importance in plant-water use at the San Dimas installation. Undoubtedly, the interface cannot be so dismissed in a more humid climate. Conceivably, it could cause a permanent water table, holding water freely available to plants throughout the growing season in a very wet climate or, given less frequent rain, as a recurring phenomenon with water freely available intermittently.

But at Tanbark Flat, water acuumulated on the soil-concrete interface only once per wet season, if at all, and there it remained until withdrawn in late summer. Unfailingly, soil at the bottoms of the San Dimas lysimeters wetted only in winter, then dried months later, but only during years when rainfall absorption exceeded "field capacity".

4. Wildland plants developed abnormally. The extensive mensurational data leaves no doubt that woody plants in large lysimeters were smaller and less thrifty than their counterparts in border strips, an effect described in detail for pine (Patric 1961b). Close evaluation to define specific effects of lysimeter walls on plant growth is beyond the scope of this study but a cursory look suggests that small plants were least influenced, presumably because their roots suffered least from confinement. This interpretation agrees with the 1972 observations of relatively successful buckwheat (the smallest plant) and failure of pine (the largest plant) to survive on large lysimeters. Under these circumstances, inferences seem unwarranted concerning the effect of plant size on water use by wildland plants. Disease of ceanothus, growth abnormality of scrub oak, stunting of pine, and fertilization of the border strips surely confounded effects of plant size on water use by these species. The pines, particularly, were little more than unhealthy saplings when the lysimeter vegetation burned. It would be especially unwise to regard their water use in large lysimeters as representing that of mature coulter pine in a natural setting with deep soil.

These limitations suggest that comparisons of water use among lysimeter-grown wildland species may have some merit but they reinforce the old doubts concerning applicability of lysimeter findings to more natural settings. Again, the pines provide a good case in point. Lysimeter-grown pine somewhat preceded other wildland species in the season of heaviest water use. It can be argued that more copious soil moisture use early in the rainy season recommends pine culture on flood-prone watersheds, thereby providing more opportunity for rain storage during late-season storms. This minor flood control advantage, however, seems offset by the tendency for greatest surface runoff from pine lysimeters. Furthermore, pine usually had dried soils least at the end of the growing season, less rain was needed to restore soils to full wetness, and more rain was potentially divertible to streamflow. But do forest-grown pines actually function this way, or was this seemingly desirable behavior predetermined by growing them in the large lysimeters? Any answer must be tentative, at best that lysimeter results must be applied with extreme caution to real-life watershed situations.

Quite the contrasting situation pertains at the renowned lysimeter installation near Coshocton, Ohio (Harrold and Driebelbis 1967). There, one of many notable hydrologic accomplishments includes the relating of soil moisture use in a grass-covered lysimeter to evaporative losses from variously managed watersheds (Mustonen and McGuinness 1967). Sound physical reasons may be advanced to account for this desirable performance; a weighing mechanism sensitive to small and frequent soil moisture changes, a natural soil profile in the lysimeters, and a soil-air interface located well beneath plant roots. The San Dimas experience points to biological advantages also enjoyed at Coshocton, the major one being small-stature plants with life spans completed each year. Other biological advantages (annual soil moisture recharge, frequent soil rewetting during the growing season, fertilization, and tillage) assure a healthy vegetation that demonstrably uses water at rates representative of evaporative losses under conventional agricultural conditions. In my opinion, the biological asset of healthy vegetation far outweighs the physical assets in making the Coshocton lysimeter results useful in so many hydrologic applications.

Perhaps the fact of excessive surface runoff is most significant of the San Dimas lysimeter results because it shaped all other results. Had lysimeter runoff approached that of natural chaparral-covered land, rainfall disposition would have changed markedly. Amounts of runoff would have fallen nearly to 0 except perhaps for bare soil. Evaporative losses would have changed least on grass and bare soils because ample water to meet their needs seems always to have been available. Soil moisture use by woody species, particularly in dry years, would have increased markedly. No longer would seepage have remained a usually negligible quantity, but would have increased in the sequence bare > grass > woody species. But even with runoff more representative of that from natural chaparral-covered land, the San Dimas lysimeters would not have produced results as hydrologically useful as those from Coshocton. The results would merely be more realistic for stunted vegetation. Thus, for the major--though not sole--reason of excessive surface runoff, hydrologic results from the San Dimas lysimeters cannot be regarded as representative of real-life situations.

The fact of enormously augmented surface runoff from the San Dimas lysimeters raises a serious question concerning the value of meticulously recorded runoff and seepage rates. These voluminous data are on strip charts stored in a federal records center. Such records are so unrepresentative of natural rainfall disposition on chaparall-covered land that further work with them seems pointless. The concept that surface runoff is rare on any undisturbed watershed (Helvey et al. 1972) has become accepted among forest hydrologists and seems equally to apply on the San Dimas Experimental Forest. On the other hand, there may be some highly specialized need for relations of rainfall to runoff from artificially prepared soil surfaces. If so, the existence of these strip chart data should be made known. If not, I recommend that they be discarded.

The San Dimas lysimeter data proved useful in a serendipitous way when they cast light on the rhetorical question, "Does transpiration decrease as the soil moisture decreases?" (Viehmeyer and Hendrickson 1955). This question has elicited a flood of response and continues to interest students of plant-water relations. For example, Penman (1970) recently stated, "There can be no serious error in assuming that all soil water is equally available for transpiration up to the stage marked by the onset of wilting". Results from San Dimas (Fig. 14) suggest that Penman's generalization holds for lysimeter-grown grass but not for the woody plants. The question has, of course, no simple answer and any attempt to respond to it must be conditioned by such factors as plant species, climate, depth and texture of soil, and degree and frequency of water replenishment. In my opinion, one would err seriously to assume that all soil water is equally available for transpiration by chaparral on deep soil in southern California's mediterranean climate. But I hasten to add that Penman's generalization does seem to hold in humid climates given soils of moderate depth, in coniferous (Patric and Stephens 1968) and hardwood forest (Patric 1973).

When planning research on water relations of trees or other large woody plants, lysimeters should be considered only if affirmative answers are possible to the following question:

1. Can the natural environment of the test plant be simulated and maintained throughout the experiment? This was a major reason for abandoning the forest lysimeter study at La Crosse, Wisconsin (Sartz 1963).

2. Are the lysimeters large enough to permit normal plant growth? The only installation known to me that may permit natural tree development is in Holland (Delj 1948). The nearly complete lack of follow-up reports from that installation causes wonder if it too, has gone the way of so many attempts to evaluate forest water relations by this means.

3. Can soil moisture use be determined accurately, either by weighing or by non-destructive sampling? This capability is especially important for determining short-term water use (Dylla and Muckell 1965).

4. Is adequate replication and experimental control possible? Results from the one lysimeter containing a single Douglas fir tree in Washington will be severely questioned on this basis.

5. Are resources available to provide for years of trouble-free observation needed to develop the full water use story for most woody species? In Arizona, for example, long term water use comparisons among grasses were invalidated by slowly developing equipment deterioration.[5/]

[5/] Personal communication. A. R. Hibbert, Tempe, Arizona.

Little perceptivity is needed to know that answers to all of these questions finally resolve to money. Lysimeter research with trees and most wildland species usually proves financially unbearable and the financial pinch begins the search for alternatives. The neutron probe, radioactive tracers, and energy budgeting offer attractive alternatives that provide flexibility in studies of forest water-use undreamed of 40 years ago. Research on small watersheds and large plots avoids the inevitable boundary problems of lysimeters. Matters of adequate experimental control and of replication usually are less expensively dealt with on forest land. In my opinion, lysimeters should be used for studies of forest-water relations only when all other research resources prove technologically unusable.

The ultimate reason for abandoning lysimeter research at San Dimas came, not from scientific deliberation of its hydrologic merit, but from decisions at the highest levels of California government. The fire of 1960 provided a mere convenient stopping point. During the 1950's, it had been decided that southern California's expanding water needs would best be met by importation from water-rich northern parts of the State. Having established this resource management policy, answers no longer were urgent for questions concerning management of chaparral watersheds and water use by wildland species. Although local resources still are relied upon, most of southern California's present and foreseeable water need will be met by importation. Nevertheless, water still is produced most cheaply from local resources. A cost of $6 per acre foot of domestic water recently was announced for the San Gabriel Valley as opposed to $63 per acre foot of imported water.[6]

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[6] Personal communication, E. L. Hamilton, Glendora, California.

So municipalities remote from the aqueducts may yet have need to manage local chaparral watersheds according to principles conceived on the San Dimas lysimeters.

EPILOGUE

One satisfaction of working with "cold" data is that the hardest work in field, office, and laboratory is done. Only thought and perserverence are needed to draw out and to express logically the relationships sensed years before. In a sense, one seeks merely to profit by and to pass along some lessons otherwise lost. And the lessons are sound; the San Dimas lysimeter results will find many uses. On the other hand, all of us have 20-20 hindsight and can find things we might have done better. But 40 years ago, this installation expressed the best thinking by some of the world's foremost authorities on soil-plant-water relations. Of course there was room for improvement, but it stemmed from unforeseeable advances in technology, not from slackness by those who conceived and carried out this research. Their job was well done.

Many people contributed to the program of lysimeter research at the San Dimas Experimental Forest. Regrettably, the list of contributors cannot be complete, but these names and functions were gleaned from the existing records.

Mr. Henry W. Anderson - routine operation

Mr. L. A. Andrews - data collection

Dr. G. B. Bodman - consultant

Dr. and Mrs. (Dr.) F. E. Clements - consultants

Dr. E. A. Colman - soils and instrumentation

Mr. J. S. Cotton - structural stress analysis

Dr. W. U. Garstka - design and construction

Mr. E. B. Goodwin - data collection

Mr. E. L. Hamilton - hydrologic & climatic data. Instrumentation

Mr. J. S. Horton - vegetation

Dr. J. Kitteredge - consultant

Mr. J. H. Patric - routine operation

Mr. L. F. Reimann - data compilation

Dr. R. M. Rice - routine operation

Mr. J. D. Sinclair - forester in charge

Dr. F. J. Viehmeyer - consultant

Dr. P. J. Zinke - routine operation

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Table 1.--Average climate for the hydrologic year, Tanbark Flat, California

Month	Precipitation[a] (inches)	Evaporation[b] (inches)	Air temperature (°F.)[c] Max.	Min.	Mean
October	1.17	5.56	102.0	25.5	60.6
November	1.96	3.60	89.5	28.0	53.7
December	5.29	2.47	84.5	21.5	49.1
January	5.13	2.30	84.0	18.0	46.4
February	5.85	2.29	83.5	22.0	47.2
March	4.46	3.37	84.0	24.0	48.8
April	2.49	4.20	81.5	26.0	53.2
May	.42	5.52	100.0	28.5	57.2
June	.11	6.95	103.0	33.0	62.9
July	.01	9.65	104.0	39.0	71.6
August	.08	9.54	107.0	38.0	71.9
September	.30	8.07	108.5	37.5	69.8
Annual	27.27	63.52	108.5	18.0	57.7

[a] 1933 - 1960.

[b] 1934 - 1963.

[c] From Reimann 1959.

Table 2.--Lysimeter planting arrangement

Wildland species name		Lysimeters planted	
Common	Scientific[a]	Large	Unconfined
Barren	--	1	--
Buckwheat	*Eriogonum fasciculatum* var. foliolosum Nutt.	4 - 6	A
Ceanothus	*Ceanothus crassifolius* Torr.	12,13,15	C
Chamise	*Adenostoma fasciculatum* Hook. and Arn.	7 - 11	B
Coulter Pine	*Pinus coulteri* Lambert	22 - 26	E
Grasses	*Agropyron caninum* (L) Beauv. *Melica imperfecta* Trin. *Poa scabrella* (Thurb.) Benth. *Stipa lepida* Hitchc.	2 and 3	--
Scrub oak	*Quercus dumosa* Nutt.	17 - 21	D
Sugar bush	*Rhus ovata* Wats.	14 and 16	--

[a] Jepson, 1921

Table 3.--Vegetation development on the San Dimas lysimeters (1951)

Species	Height (inches)		Litter cover (percent)		Density (percent)	
	large	unconfined	large	unconfined	large	unconfined
Buckwheat	36	48	34	95	20	85
Ceanothus	48	58	64	91	23	67
Chamise	19	31	10	15	16	35
Coulter pine	55	88	26	35	10	22
Scrub oak	erratic		40	95	27	87

Table 4.--Chronology of major lysimeter events

Event	Date
Work began on lysimeter site	January 1934
Soil mixing completed	January 1936
Roof built over large lysimeters	October 1936
Large lysimeters filled with soil	December 1936
Deer- and rodent-proof fence completed	April 1937
Unconfined lysimeters filled with soil	October 1937
All lysimeters covered with excelsior	October 1937
Seepage began from large lysimeters	February 1938
First weeding	May 1938
Climatic station installed	June 1938
Surface runoff and seepage recorders installed on 15 lysimeters	1939
Overfill removed	July 1940
Grass planted	October 1940
Observation under grass ended	January 1946
Wildland species planted	February 1946
Roots permeating all lysimeter soils	August 1947
Colman units installed in 8 large and all unconfined lysimeters	1951-52
Grass planted in lysimeters 2 and 3	January 1951
Sugar bush planted in lysimeters 14 and 16	January 1952
Lysimeters operating as designed under vigorous wildland species	1953-1959
Lysimeter vegetation, fence, wiring, etc. destroyed by wildfire	July 1960

Table 5.--Surface runoff from the grass-covered lysimeters and from chaparral-covered plots at two locations on the San Dimas Experimental Forest

Year	Rainfall	Lysimeters		Plots[a]	
		large	unconfined	Tanbark Flat	Fern Canyon
	inches				
1940-41	48.23	36.55	31.41	0.10	0.60
1941-42	16.65	3.04	2.34	T	T
1942-43	45.23	24.05	18.76	0.10	0.20
1943-44	33.46	14.80	10.82	T	0.40
1944-45	29.65	10.37	7.02	T	0.10

[a] From Rowe et al. 1954

Table 6.--Water content-tension relations[a] in the original San Dimas lysimeter soil

Soil water tension	Inches of water per inch of soil	Water content of lysimeter soil Large (72")	Unconfined (120")
Bars	% H_2O by volume	------------inches	--------------
0.05	0.409	29.45	49.08
.10	.335	24.12	40.02
.25	.257	18.50	30.84
.33	.237	17.06	28.44
.50	.199	14.33	23.88
1.00	.165	11.88	19.80
3.00	.143	10.30	17.16
7.00	.131	9.43	15.72
10.00	.112	8.06	13.44
15.00	.104	7.49	12.48

[a] Furnished by Dr. Leonard De Bano (U.S.F.S., Glendora, Calif.). Derived from pressure extraction, using stored samples of the original lysimeter soil.

APPENDIX

Table 7.--Phenology of plants on large lysimeters containing Colman units, H. Y. 1958-59

Date	Stage of Growth
	GRASS (LYSIMETERS 3)
October 8, 1958	Dormant
October 15, 1958	New growth started
November 8, 1958	Large grass 16 inches high
	Small grasses 8 inches high
November 20, 1958	
to March 3, 1959	Recurrent measurements of plant height.
	Large grass to 20 inches, small grass to 12 inches.
March 10, 1959	Annual grasses invading
April 15, 1959	Grass heading out
May 5, 1959	Heading out complete
May 19, 1959	Grass turning brown
June 23, 1959	A few larger grass stems remain green.
	All others are brown.
July 14, 1959	All grass is brown.
November 2, 1959	Dormant
November 9, 1959	New growth started

Continued

Table 7.--continued

BUCKWHEAT (LYSIMETER 5)	
October 8, 1958 to March 31, 1959	Dormant
April 7, 1959	New growth started
May 5, 1959	Flower buds forming
May 26, 1959	Blossoming begins
June 23, 1959	All plants in bloom
July 28, 1959	Flowers turning brown
August 4, 1959	This year's growth wilted
September 1, 1959	Dormant
CHAMISE (LYSIMETER 9)	
October 8, 1958 to March 10, 1959	Dormant
March 24, 1959	New growth starting
May 5, 1959	New growth on all plants up to 2-1/2 inches
May 19, 1959	New growth ceased
May 26, 1959	Flower buds swelling
June 16, 1959	Blossoming
July 7, 1959	Blossoms turning brown
July 21, 1959	Some leaves turning brown
August 4, 1959	This year's growth hardened
September 1, 1959	Dormant

Continued

Table 7.--continued

SUGAR BUSH (LYSIMETER 14)	
October 8, 1958 to October 31, 1958	Dormant
November 20, 1958	Flower buds forming, some new growth
November 27, 1958	Dormant
January 23, 1959	Flower buds swelling
March 10, 1959	Dormant
April 15, 1959	Some flowering
July 7, 1959	Up to 4 inches new growth on all plants.
August 4, 1959	Growth about complete.
August 25, 1959	Dormant
CEANOTHUS (LYSIMETER 15)	
October 8-31, 1958	Large plants hardened, some growth continuing on smaller plants.
November 8, 1959 to March 3, 1959	Dormant
March 3, 1959	Buds swelling
March 24, 1959	All plants in full bloom
April 15, 1959	Flowers browning, new growth beginning.
May 5, 1959	Growth continuing, seed forming.
July 7, 1959	Not much new growth, seed pods bursting.
August 4, 1959	This year's growth hardened.
September 1, 1959	Dormant

Continued

Table 7.--continued

SCRUB OAK (LYSIMETER 19)	
October 8, 1958 to March 10, 1959	Dormant
April 15, 1959	New growth on about 50 percent of all plants
April 21 to June 2, 1959	New growth continuing
June 16, 1959	New growth hardening
July 7, 1959	No new growth
August 4, 1959	All plants hardened
August 25, 1959	Dormant
COULTER PINE (LYSIMETER 24)	
October 8, 1958 to February 28, 1959	Dormant. Some needles browning.
March 5, 1959	Some buds swelling
March 10, 1959	All buds elongating
April 7, 1959	New growth (candles) 1 to 2-1/2 inches long
April 24, 1959	New needle growth beginning
April 28 to June 23, 1959	New growth continuing
July 7, 1959	No new growth
July 28, 1959	All new growth hardened
August 4, 1959	New buds formed
September 1, 1959	Dormant

WATER CONTENT

Maximum water content in 6 feet of lysimeter soil was measured on April 4, 1958. Measurement (by Colman units) was immediately after 8 inches of rain had fallen during the 4 previous days, on soils already very wet and yielding seepage flow. Water was so mobile in soil of this wetness that measurements at any depth were apt to drift over short time periods.

Large Lysimeters		Unconfined Lysimeters	
No.	Water content (inches)	No.	Water content (inches)
5	25.15	A	23.13
9	24.69	B	23.89
15	26.78	C	23.10
19	24.53	D	22.28
24	25.27	E	21.96
Average	25.28	Average	22.87

These data suggest that about 2-1/2 inches of water were held on the soil-concrete interface of large lysimeters. All large lysimeters were seeping at the time of soil moisture measurement. Presumably, a little more water would be stored on the interface just before the onset of seepage, a little less just as it stopped.

Table 8.--Interception loss (IL) equations

Plant	Equation	Source	Comments
Chaparral	IL = 0.62P + 0.83	Hamilton and Rowe 1949	This equation was used for brush species.
Coulter Pine	IL = .046P + .034	Hoover 1953	This equation was developed for 10-year-old loblolly pine, about the same in structure, size, age, and appearance as coulter pine.
Grass	IL = .032P + .074	Corbett and Crouse 1968	The single equation was used yearlong because grass phenologies for most years were unavailable.
Excelsior	IL = .01P + .05	Derived	By trial and error I found that this equation would provide annual interception losses for San Dimas rainfall approaching those reported by Rowe (1955) for 2.7 inches of ponderosa pine litter.

Table 9.--Annual hydrologic data for all lysimeters, in inches

Year	Lysimeter numbers	Runoff	Seepage	Interception loss	Soil moisture loss	Total evaporative loss	Precipitation	Class A pan evaporation
	Large lysimeters						Climatic data	
				EXCELSIOR				
1938-39	All	7.69	4.13	3.32	6.53	9.85	21.67	72.65
1939-40	All	14.77	4.08	3.85	4.54	8.39	27.24	77.68
				BARE				
1940-41	1	37.04	0.58	0	10.61	10.61	48.23	61.39
1941-42	1	8.05	0	0	8.60	8.60	16.65	70.08
1942-43	1	35.73	0	0	9.50	9.50	45.23	70.08
1943-44	1	23.82	.06	0	9.58	9.58	33.46	59.73
1944-45	1	18.24	0	0	11.41	11.41	29.65	59.83
1945-46	1	15.18	.11	0	11.56	11.56	26.85	63.39
1946-47	1	19.22	0	0	8.46	8.46	27.68	63.54
1947-48	1	9.50	0	0	6.33	6.33	15.83	69.95
1948-49	1	6.83	0	0	10.11	10.11	16.94	64.67
1949-50	1	13.39	0	0	7.39	7.39	20.78	64.13
1950-51	1	5.00	0	0	6.47	6.47	11.47	72.42
1951-52	1	31.59	0	0	9.51	9.51	41.10	57.52
1952-53	1	8.44	0	0	7.03	7.03	15.47	61.46
1953-54	1	18.49	0	0	6.43	6.43	24.92	61.38
1954-55	1	11.52	0	0	8.42	8.42	19.94	61.40
1955-56	1	13.00	0	0	7.18	7.18	20.18	60.84
1956-57	1	11.61	0	0	8.20	8.20	19.81	59.87
1957-58	1	39.15	.04	0	8.89	8.89	48.08	50.16
1958-59	1	10.80	0	0	3.54	3.54	14.34	53.58

Table 9.--(Cont) Patric : 112a

	Large lysimeters						Unconfined lysimeters		
Year	Lysimeter numbers	Runoff	Seepage	Interception loss	Soil moisture loss	Total evapor-ative loss	Lysimeter numbers	Runoff	Infiltra-tion
				GRASS					
1940-41	2-26	36.55	0.02	3.92	7.74	11.66	A-E	30.41	13.79
1941-42	2-26	3.04	0	2.24	11.37	13.61	A-E	2.34	12.91
1942-43	2-26	24.05	2.43	2.82	15.93	18.75	A-E	18.76	22.69
1943-44	2-26	14.80	2.95	3.03	12.68	15.71	A-E	10.82	19.75
1944-45	2-26	10.37	2.54	2.63	14.11	14.74	A-E	7.02	20.08
1951-52	2&3	17.20	.96	3.05	19.89	22.94	--	--	--
1952-53	2&3	1.46	1.13	2.13	10.75	12.88	--	--	--
1953-54	2&3	8.72	3.10	1.84	11.26	13.10	--	--	--
1954-55	2&3	1.45	1.35	2.22	14.92	17.14	--	--	--
1955-56	2&3	4.37	1.25	2.01	12.55	14.56	--	--	--
1956-57	2&3	.74	2.31	2.20	14.56	16.76	--	--	--
1957-58	2&3	20.79	11.49	3.60	12.20	15.80	--	--	--
1958-59	2&3	2.24	.47	1.33	10.30	11.63	--		
				BUCKWHEAT					
1946-47	2-6	8.65	0.77	0	18.26	18.26	A	8.49	19.19
1947-48	2-6	4.86	0	0	10.97	10.97	A	1.24	14.59
1948-49	2-6	.81	0	1.49	14.64	16.13	A	0	15.45
1949-50	2-6	4.49	0	1.29	15.00	16.29	A	2.30	17.19
1950-51	2-6	.73	0	1.91	8.83	10.74	A	.03	9.53
1951-52	4,5,6	16.30	.83	4.43	19.54	23.97	A	12.45	24.22
1952-53	4,5,6	1.14	0	2.56	11.77	14.33	A	.11	12.80
1953-54	4,5,6	7.19	0	2.70	15.03	17.73	A	2.88	19.34
1954-55	4,5,6	2.01	0	2.85	15.08	17.93	A	.01	17.08
1955-56	4,5,6	3.32	0	2.62	14.24	16.86	A	.68	16.88
1956-57	4,5,6	.72	0	2.91	16.18	19.09	A	.10	16.80
1957-58	4,5,6	19.67	4.09	5.28	19.04	24.32	A	13.06	29.74
1958-59	4,5,6	2.60	0	1.77	9.97	11.74	A	.69	11.88

Table 9.--(cont)

Year	Large lysimeters: Lysimeter numbers	Runoff	Seepage	Interception loss	Soil moisture loss	Total evapor-ative loss	Unconfined lysimeters: Lysimeter numbers	Runoff	Infiltra-tion
					CHAMISE				
1946-47	7-11	11.20	0.67	0	15.81	15.81	B	11.51	16.17
1947-48	7-11	6.89	0	0	8.94	8.94	B	4.63	11.20
1948-49	7-11	.89	0	1.98	14.07	16.05	B	.73	14.23
1949-50	7-11	6.32	0	1.28	13.18	14.46	B	2.81	16.69
1950-51	7-11	1.26	0	1.91	8.30	10.21	B	.07	9.49
1951-52	7-11	17.67	.37	4.39	18.67	23.06	B	11.37	25.34
1952-53	7-11	2.70	0	2.58	10.19	12.77	B	.72	12.17
1953-54	7-11	8.61	0	2.71	13.60	16.31	B	2.89	19.32
1954-55	7-11	2.89	0	2.86	14.19	17.05	B	.58	16.50
1955-56	7-11	3.91	0	2.60	13.67	16.27	B	.89	16.69
1956-57	7-11	2.12	0	2.89	14.80	17.69	B	.46	16.46
1957-58	7-11	19.14	3.35	5.27	20.32	25.59	B	9.61	33.20
1958-59	7-11	2.01	0	1.78	10.55	12.33	B	1.05	11.51
					CEANOTHUS				
1946-47	12,13,15	13.16	2.28	0	12.24	12.24	C	11.31	16.37
1947-48	12,13,15	7.09	0	0	8.74	8.74	C	4.85	10.98
1948-49	12,13,15	2.62	0	1.49	12.83	14.32	C	1.33	14.12
1949-50	12,13,15	6.64	0	1.28	12.86	14.14	C	4.56	14.94
1950-51	12,13,15	1.17	0	1.91	8.39	10.30	C	.11	9.45
1951-52	12,13,15	17.34	.57	4.39	18.80	23.19	C	16.46	20.25
1952-53	12,13,15	1.56	0	2.57	11.34	13.91	C	.52	12.38
1953-54	12,13,15	6.65	0	2.71	15.56	18.27	C	12.70	9.51
1954-55	12,13,15	1.43	0	2.84	15.67	18.51	C	1.32	15.78
1955-56	12,13,15	2.95	0	2.62	14.61	17.23	C	3.89	13.67
1956-57	12,13,15	.40	0	2.89	16.52	19.41	C	.37	16.55
1957-58	12,13,15	18.37	4.67	5.28	19.76	25.04	C	16.72	26.08
1958-59	12,13,15	2.07	0	1.76	10.51	12.27	C	2.28	10.30
1946-47	14&16	13.37	1.07	0	13.24	13.24	--	--	--
1947-48	14&16	7.22	0	0	8.61	8.61	--	--	--
1948-49	14&16	2.41	0	1.48	13.05	14.53	--	--	--
1949-50	14&16	6.23	0	1.29	13.26	14.55	--	--	--
1950-51	14&16	1.13	0	1.90	8.44	10.34	--	--	--
1951-52	14&16	17.71	1.39	4.42	17.58	22.00	--	--	--

Table 9.--(cont)

Year	Large lysimeters: Lysimeter numbers	Runoff	Seepage	Interception loss	Soil moisture loss	Total evapor- ative loss	Unconfined lysimeters: Lysimeter numbers	Runoff	Infiltra- tion
				SUGARBUSH					
1952-53	14&16	2.77	0.99	0	11.71	11.71	--	--	--
1953-54	14&16	7.42	0	1.34	16.16	17.50	--	--	--
1954-55	14&16	2.62	0	1.45	15.87	17.32	--	--	--
1955-56	14&16	4.08	0	2.61	13.49	16.10	--	--	--
1956-57	14&16	1.19	0	2.88	15.74	18.62	--	--	--
1957-58	14&16	21.79	2.34	5.32	18.63	23.95	--	--	--
1958-59	14&16	2.43	0	1.79	10.12	11.91	--	--	--
				SCRUB OAK					
1946-47	17-21	12.95	1.18	0	13.55	13.55	D	13.34	14.34
1947-48	17-21	6.68	0	0	9.15	9.15	D	5.13	10.70
1948-49	17-21	1.29	0	1.49	14.16	15.65	D	.43	15.02
1949-50	17-21	4.92	0	1.28	14.58	15.86	D	2.54	16.96
1950-51	17-21	.68	0	1.91	8.88	10.79	D	.53	9.03
1951-52	17-21	17.97	1.26	4.40	17.47	21.87	D	19.26	17.44
1952-53	17-21	.91	0	2.60	11.96	14.56	D	.39	12.48
1953-54	17-21	5.74	0	2.69	16.49	19.18	D	5.94	16.29
1954-55	17-21	1.40	0	2.88	15.66	18.54	D	.92	16.14
1955-56	17-21	2.81	0	2.62	14.75	17.37	D	3.96	13.60
1956-57	17-21	.32	0	2.92	16.57	19.49	D	1.56	15.33
1957-58	17-21	15.04	5.28	5.24	22.52	27.76	D	25.56	17.28
1958-59	17-21	2.10	0	1.78	10.46	12.24	D	3.61	8.95
				PINE					
1946-47	22-26	9.84	0.22	0	17.62	17.62	E	8.18	19.50
1947-48	22-26	7.12	0	0	8.71	8.71	E	5.05	10.78
1948-49	22-26	2.52	0	0.84	13.58	14.42	E	1.82	14.28
1949-50	22-26	7.29	0	.75	12.74	13.49	E	7.24	12.79
1950-51	22-26	2.15	0	1.11	8.21	9.32	E	1.74	8.62
1951-52	22-26	18.84	.26	2.71	19.29	22.00	E	18.69	19.70
1952-53	22-26	3.48	0	1.49	10.50	11.99	E	3.99	9.99
1953-54	22-26	10.08	0	1.72	13.12	14.84	E	10.31	12.89
1954-55	22-26	4.13	0	1.60	14.21	15.81	E	4.93	13.41
1955-56	22-26	5.36	0	1.54	13.28	14.82	E	6.19	12.45
1956-57	22-26	2.38	0	1.70	15.73	17.43	E	2.07	16.04
1957-58	22-26	17.26	5.63	3.27	21.92	25.19	E	12.82	31.99
1958-59	22-26	3.43	0	1.05	9.86	10.91	E	2.17	11.12

Table 10.--Water content of lysimeter soils at the end of each growing season after establishing their permanent vegetative cover

Year	Large lysimeters								Unconfined lysimeters				
	1	3	5	8	14	16	19	24	A	B	C	D	E
	Inches Water in 6 feet of soil												
1947	15.0	--	6.5	6.7	6.6	--	9.9	7.7	--	--	--	--	--
1948	14.2	--	5.6	6.6	6.0	--	6.1	7.3	--	--	--	--	--
1949	15.8	--	5.7	6.1	5.8	--	6.3	6.8	--	--	--	6.3	6.9
1950	15.2	--	5.6	6.0	5.8	--	6.5	6.6	--	--	--	6.9	6.8
1951	14.2	6.8[a]	5.8	5.7	6.5	--	6.1	6.4	--	--	--	6.5	6.5
									Inches water in 10 feet of soil				
1952	15.4	16.5	6.1	5.9	6.6	6.4	8.2	7.5	10.4	11.8	14.1	13.3	12.9[b]
1953	15.6	17.4	5.8	5.8	5.8	5.7	6.2	6.6	10.2	9.6	9.5	10.9	11.0
1954	15.0	15.6	5.7	6.0	5.8	7.8	6.4	7.6	11.0	10.4	9.9	11.4	11.2
1955	15.9	16.4	6.5	6.1	8.4	7.1	7.3	7.3	11.9	10.7	10.1	11.5	11.1
1956	17.9	15.8	6.3	6.3	8.2	6.9	7.8	7.7	11.8	10.8	10.0	11.5	11.2
1957	19.2	15.7	6.5	6.2	9.2	7.6	7.5	9.2	12.3	10.9	10.5	11.7	12.8
1958	20.4	16.2	7.5	7.1	10.0	9.1	8.1	9.3	14.8	15.3	13.5	15.9	14.2
1959	18.9	16.2	6.4	6.2	8.0	7.1	7.6	8.5	13.0	12.0	11.3	12.5	12.6
$\bar{x}$	16.4	16.2	6.2	6.2	7.1	7.2	7.2	7.5	11.9	11.4	11.1	12.3	12.1
S_x	$\pm$2.0	$\pm$0.6	$\pm$0.5	$\pm$0.4	$\pm$1.5	$\pm$1.0	$\pm$1.1	$\pm$1.9	$\pm$1.5	$\pm$1.7	$\pm$1.7	$\pm$1.6	$\pm$1.1

a/ This value for buckwheat. Grass planted next growing season.

b/ Colman units installed to at least 114 inches soil depth in all unconfined lysimeters.

Table 11.--A comparison between methods used to estimate water content in 6 feet of lysimeter soil. Each table entry is the average difference (Colman unit-gravimetric) among all paired comparisons on record

Vegetative cover	Large lysimeter		Unconfined lysimeter	
Bare	+0.52*	(12)[a/]	--	--
Grass	+0.08	(13)	--	--
Buckwheat	-0.08	(13)	+0.43	(7)
Chamise	+0.40	(13)	-0.70*	(5)
Sugarbush	+0.43*	(14)	--	--
Ceanothus	-0.09	(9)	-0.87	(8)
Scrub oak	-0.03	(16)	+0.08	(12)
Coulter pine	+0.31*	(17)	+0.25	(11)

* Significant, .05 level of probability.

[a/] Number of paired comparisons is listed in parentheses.

Table 12.--Wet and dry year soil moisture losses (inches) from large lysimeters. These monthly soil moisture loss estimates are based on Colman unit readings at about 2-week intervals

Surface	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Year
						WET YEAR (1957-58)							
Class A pan	3.19	2.15	1.76	2.25	1.62	1.59	4.00	5.75	6.41	7.81	7.11	6.52	50.16
Bare	.52	.95	.49	.57	1.68	1.38	1.50	.51	.72	.46	.48	.47	9.73
Grass	.49	.97	1.37	2.32	2.04	.69	2.54	2.22	2.24	.59	.47	1.13	17.07
Coulter pine	.68	1.46	2.73[a]	.51	2.89	.47	3.53	3.61	3.05	5.13	1.84	.22	26.12
All chaparral	.59	1.37	2.02	.63	2.40	1.62	3.39	2.96	3.18	2.98	2.72	2.44	26.30
						MEAN OF 6 DRY YEARS (1952-1957, 1958-59)							
Class A pan	5.62	3.30	2.38	1.70	2.66	3.51	3.91	4.73	6.53	9.05	8.84	7.91	60.14
Bare	.23	.46	.62	.96	.66	.75	.96	1.05	.70	.63	.63	.36	8.01
Grass	.61	.91	.51	1.02	1.56	1.97	1.99	1.82	2.67	1.16	.81	.27	15.30
Coulter pine	.24	.47	.85	1.71	2.15	2.44	1.34	2.55	2.06	1.44	.88	.24	16.37
All chaparral	.39	.44	.46	.91	1.80	1.58	1.28	1.59	2.68	2.89	1.57	.52	16.08

[a] Evaporative losses of soil moisture far exceeding pan evaporation are not likely to have occurred and are shown as equal to pan evaporation in Figure 11.

Table 13.--Dry-year soil moisture loss (inches) from unconfined lysimeters. These monthly loss estimates are based on Colman unit readings at about 2-week intervals

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Year
					MEAN OF 4 CHAPARRAL SPECIES								
1952-53	1.87	1.43	2.15	1.93	1.45	1.56	2.47	3.19	2.44	2.18	0.48	0.07	21.22
1953-54	.07	1.01	1.13	1.66	.36	1.80	1.20	2.51	4.41	3.47	1.64	.62	19.88
1954-55	.10	.45	1.10	2.14	2.23	1.80	1.33	2.47	4.09	2.79	1.73	.54	20.77
1955-56	.31	0	.32	2.00	1.84	1.01	1.71	2.35	4.49	2.55	1.52	.87	18.97
1956-57	.25	.11	.25	1.24	1.21	1.59	1.45	1.30	5.19	4.28	1.58	.65	19.10
Average of all dry years	0.52	0.60	0.99	1.79	1.42	1.55	1.63	2.36	4.12	3.05	1.39	0.55	19.98
						PINE ONLY							
1952-53	.72	2.45	.51	2.31	2.53	1.23	1.32	1.21	.77	.98	.31	0	14.34
1953-54	0	.35	.40	.61	1.94	2.70	3.32	1.49	.84	.85	.51	.33	13.34
1954-55	.09	.38	1.17	.43	3.52	2.33	.44	1.71	1.63	.87	.39	.19	13.15
1955-56	.22	.13	.75	0	.31	2.93	2.85	2.23	1.15	.65	.40	.20	11.82
1956-57	.04	.20	.19	.91	1.07	1.90	1.17	.67	3.98	4.02	.47	.41	15.03
Average of all dry years	0.21	0.70	0.60	0.85	1.87	2.22	1.82	1.46	1.67	1.47	0.42	0.23	13.53

Table 14.--Some selected water balance data for the San Dimas large lysimeters, in inches

Lysimeter number	Precipitation (P)	Surface runoff (R)	Seepage (S)	Evapotranspiration ET = P - (R+S)
UNDER EXCELSIOR (1939-1940)				
1	26.46	13.64	4.59	8.23
2		18.57	1.38	6.51
3		12.48	5.34	8.64
4		16.39	3.08	6.99
5		15.96	4.10	6.40
6		15.86	3.75	6.85
7		15.70	3.41	7.35
8		15.15	4.36	6.95
9		12.96	5.02	8.48
10		14.06	4.76	7.64
11		15.79	2.98	7.69
12		15.55	3.89	7.02
13		11.74	5.14	9.58
14		16.06	4.38	6.02
15		14.10	5.14	7.22
16		14.79	4.08	7.59
17		15.05	4.47	6.94
18		13.43	4.83	8.20
19		14.19	4.53	7.74
20		15.77	3.42	7.27
21		13.11	4.15	9.20
22		16.17	3.60	6.69
23		14.73	3.77	7.96
24		15.82	4.10	6.54
25		11.49	4.22	10.75
26		16.27	3.52	6.67
Average	26.46	14.80	4.08	7.58

Lysimeter number	Precipitation (P)	Surface runoff (R)	Seepage (S)	Evapotranspiration ET - P - (R+S)
UNDER GRASS (1944-1945)				
1 (Bare)	29.65	18.75	0	10.90
2		10.16	1.62	17.87
3		6.52	.05	23.08
4		8.31	1.09	20.25
5		9.21	.98	19.46
6		8.82	1.10	19.73
7		9.81	1.73	18.11
8		8.50	1.05	20.10
9		9.08	.92	19.65
10		10.75	1.78	17.12
11		11.46	2.66	15.53
12		11.15	2.46	16.04
13		11.82	2.37	15.46
14		11.44	2.79	15.42
15		10.35	1.92	17.38
16		11.61	2.30	15.74
17		11.65	2.12	15.88
18		11.65	2.84	15.16
19		11.44	2.29	15.92
20		11.62	2.95	15.08
21		11.77	3.47	14.41
22		11.85	3.26	14.54
23		11.44	3.76	14.45
24		11.56	3.25	14.84
25		11.88	3.37	14.40
26		11.81	3.16	14.68
Average	29.65	10.63	2.21	16.81

Table 14.--(Cont)

Lysimeter number	Precipitation (P)	Surface runoff (R)	Seepage (S)	Evapotranspiratio ET - P - (R+S)
UNDER WILDLAND SPECIES IN A WET YEAR (1957-1958)				
1 (Bare)	48.08	39.14	0.04	8.90
2		21.27	11.56	15.25
3		20.28	11.49	16.31
Average grass		20.77	11.53	15.78
4		19.30	5.21	23.57
5		20.88	2.61	24.59
6		21.03	4.46	22.59
Average buckwheat		20.40	4.09	23.59
7		19.46	3.09	25.53
8		19.86	3.23	24.99
9		18.75	3.87	25.46
10		19.51	3.19	25.38
11		18.90	3.36	25.82
Average chamise		19.30	3.35	25.43
12		17.20	4.56	26.32
13		19.39	4.38	24.31
15		18.59	5.08	24.41
Average ceanothus		18.39	4.67	25.02
14		22.02	2.50	23.56
16		21.59	2.20	24.29
Average sugarbush		21.81	2.35	23.92

Table 14.--(Cont)

Lysimeter number	Precipitation (P)	Surface runoff (R)	Seepage (S)	Evapotranspiration ET - P - (R+S)
17		16.71	6.92	24.45
18		16.20	8.35	23.53
19		19.42	3.81	24.85
20		17.52	7.24	23.32
21		13.12	16.62	18.34
Average scrub oak		16.59	8.59	22.90
22		16.22	5.62	26.24
23		17.30	6.53	24.25
24		16.97	7.35	23.76
25		18.19	3.92	25.97
26		18.15	4.71	25.22
Average coulter pine		17.37	5.63	25.08
UNDER WILDLAND SPECIES IN A DRY YEAR (1958-59)				
1	14.34	10.77	0	3.57
2		2.07	0.62	11.65
3		2.41	.53	11.40
Average grass		2.24	0.57	11.53
4		2.07	0	12.27
5		2.40	0	11.94
6		2.09	0	12.25
Average buckwheat		2.19	0	12.15

Table 14.--(Cont)

Lysimeter number	Precipitation (P)	Surface runoff (R)	Seepage (S)	Evapotranspiration ET - P - (R+S)
7		1.73	0	12.61
8		2.50	0	11.84
9		1.64	0	12.70
10		1.99	0	12.35
11		1.76	0	12.58
Average chamise		1.92	0	12.42
12		1.87	0	12.47
13		1.78	0	12.56
15		1.97	0	12.37
Average ceanothus		1.87	0	12.47
14		2.27	0	12.07
16		2.54	0	11.80
Average sugarbush		2.40	0	11.94
17		1.52	0	12.82
18		1.64	0	12.70
19		1.69	0	12.65
20		1.66	0	12.68
21		1.58	0	12.76
Average scrub oak		1.62	0	12.72
22		2.42	0	11.92
23		2.78	0	11.56
24		2.66	0	11.68
25		3.53	0	10.81
26		2.67	0	11.67
Average coulter pine		2.81	0	11.53

Figure 1.--Tanbark Flat and nearby mountains. The lysimeters were under construction on the cleared area near the center of this picture. Skyline elevation is about 3,500 feet. The conifers, mostly coulter pine, were planted on better sites after the native chaparral had been cleared. Photo by E. L. Hamilton, USFS.

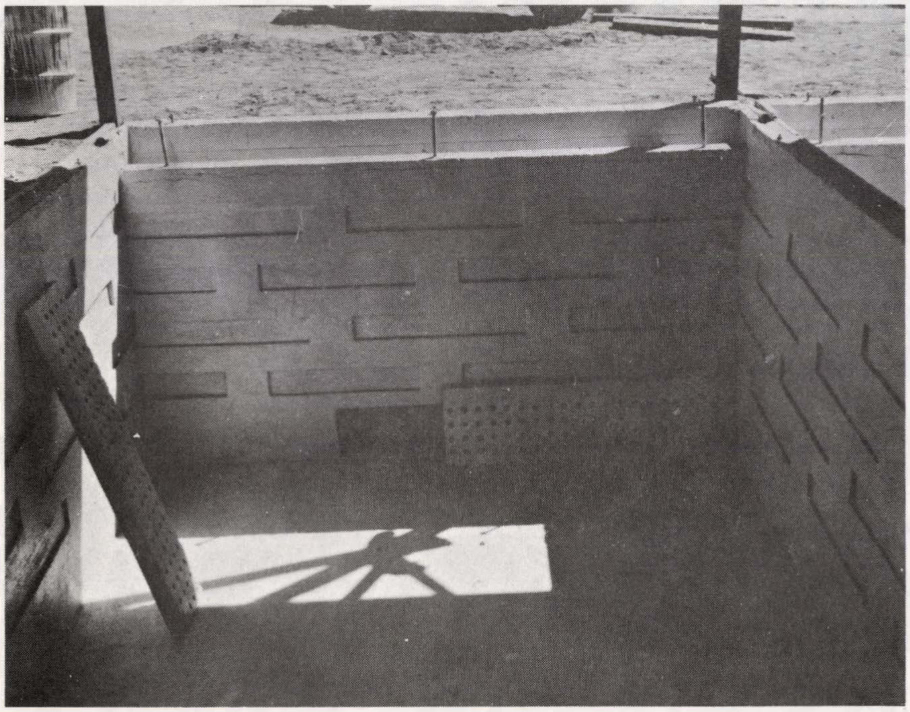


Figure 2.--A large lysimeter before filling with soil, viewed along its long axis. The wall recesses were intended to impede water flow between concrete and soil. Note seepage opening and perforated cover plates on lysimeter bottom, and surface runoff trough on top of most distant wall. Photo by E. A. Colman, USFS.

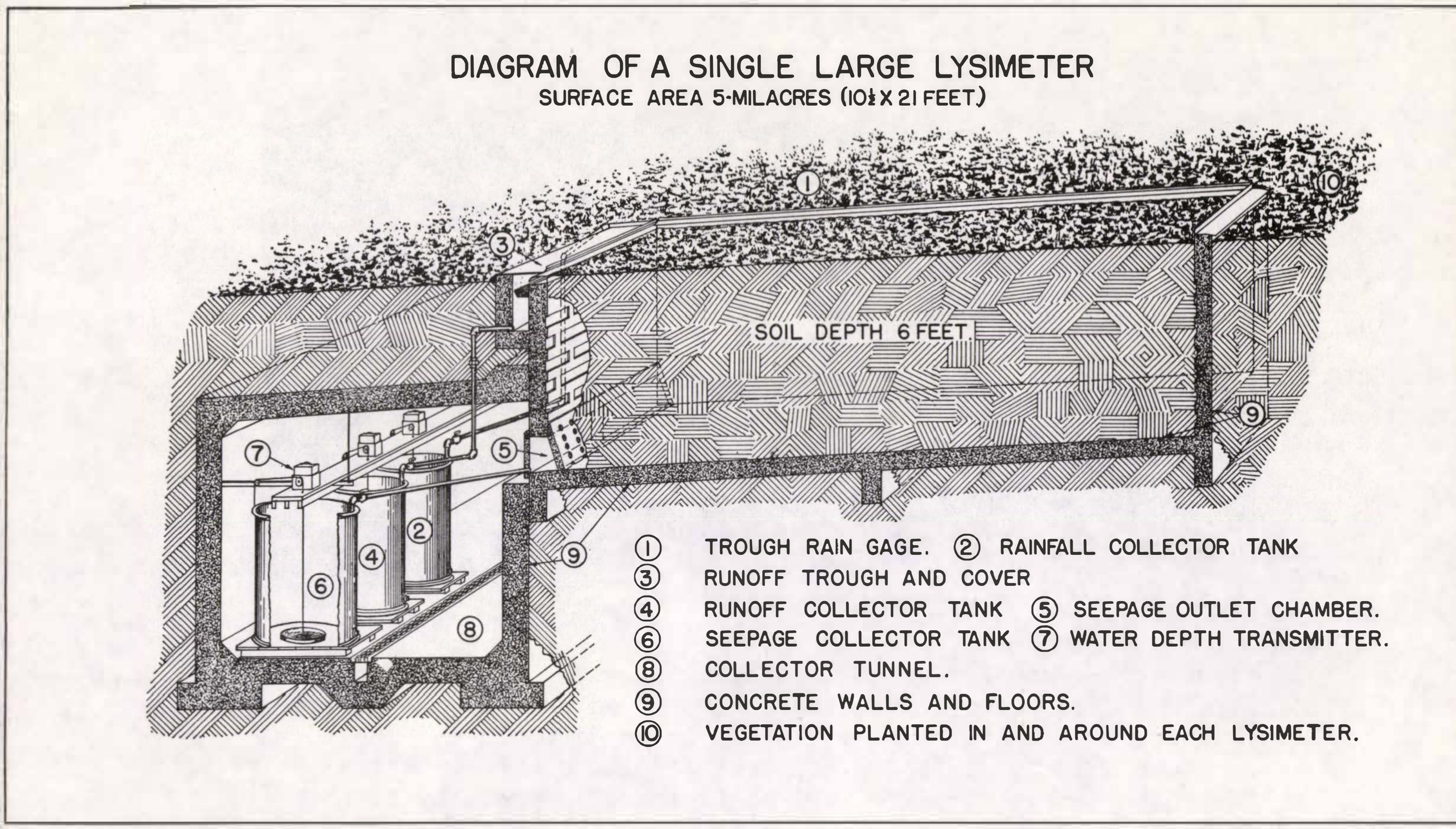


Figure 3.--Diagram of a single large lysimeter.

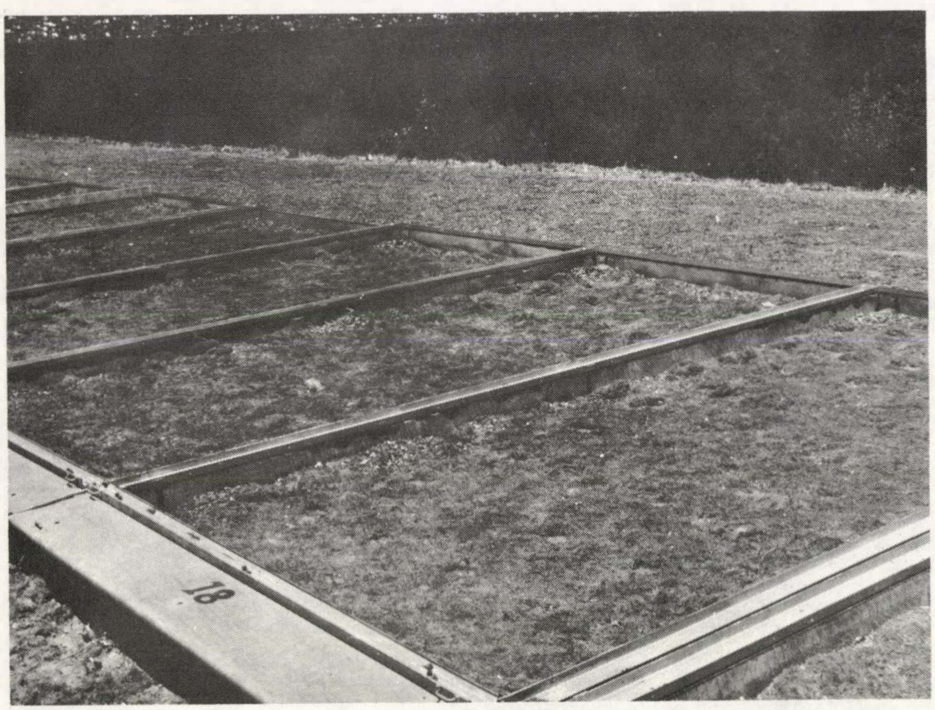


Figure 4.--The excelsior cover just before removal in 1940. Note trough rain gages on top of lysimeter walls. The numbered covers could be raised to clean out surface runoff collectors. Photo by E. L. Hamilton, USFS.

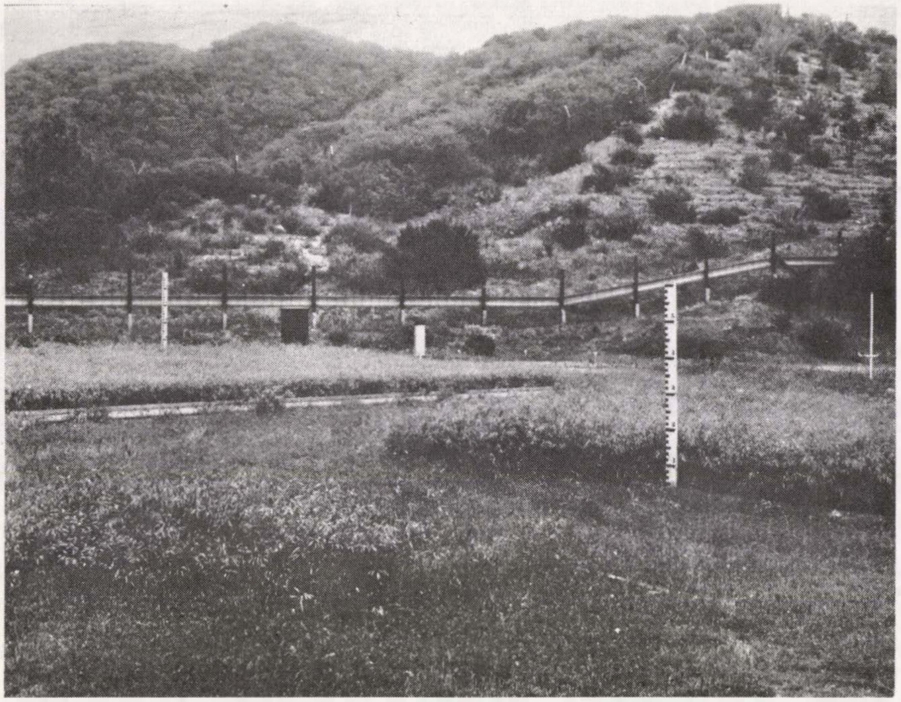


Figure 5.--The grass cover was complete but varied from year to year in vigor. Unconfined lysimeter E is in the right foreground, large lysimeters 24, 25, and 26 are behind it and extend to the left. Subsequently, border areas surrounding the lysimeters were fertilized with 150 pounds per acre of ammonium phosphate to stimulate growth of grass on them. Note deer- and rodent-proof fence surrounding the lysimeter enclosure. Photo by J.S. Horton, USFS.

Figure 6.--Coulter pines in large lysimeters 22 and 23. The trees in the border planting are much larger, an effect almost certainly caused by unrestricted root growth and possibly by fertilization. These trees were thinned to 5 per lysimeter shortly aft after this picture was taken. The surveying rod was extended to 15 feet. Shrub in left foreground is scrub oak. Photo by J.H. Patric, USFS.

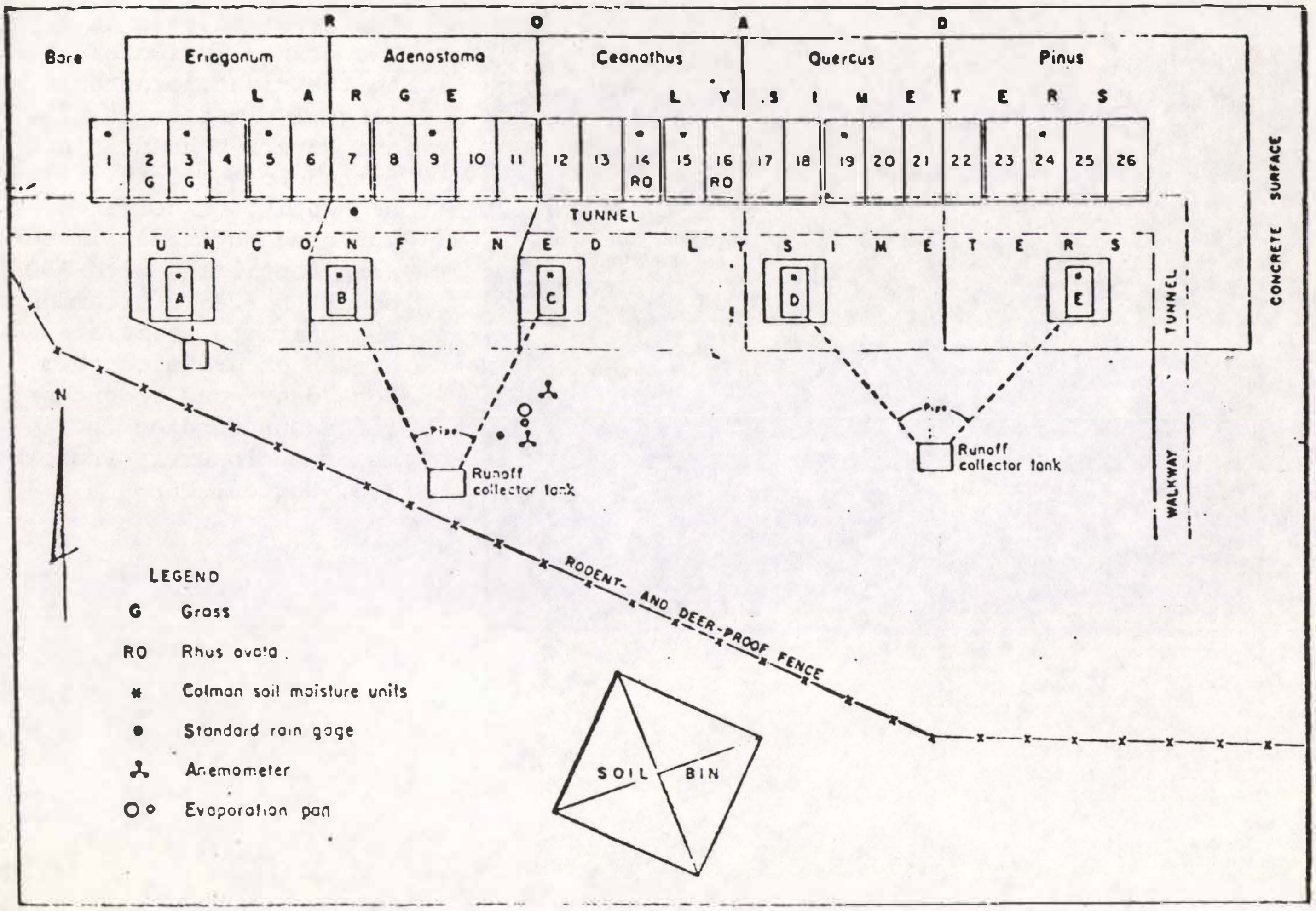


Figure 7.--Plan of lysimeter enclosure at Tanbark Flat.

Figure 8.--Vegetation effects on annual runoff from large lysimeters.

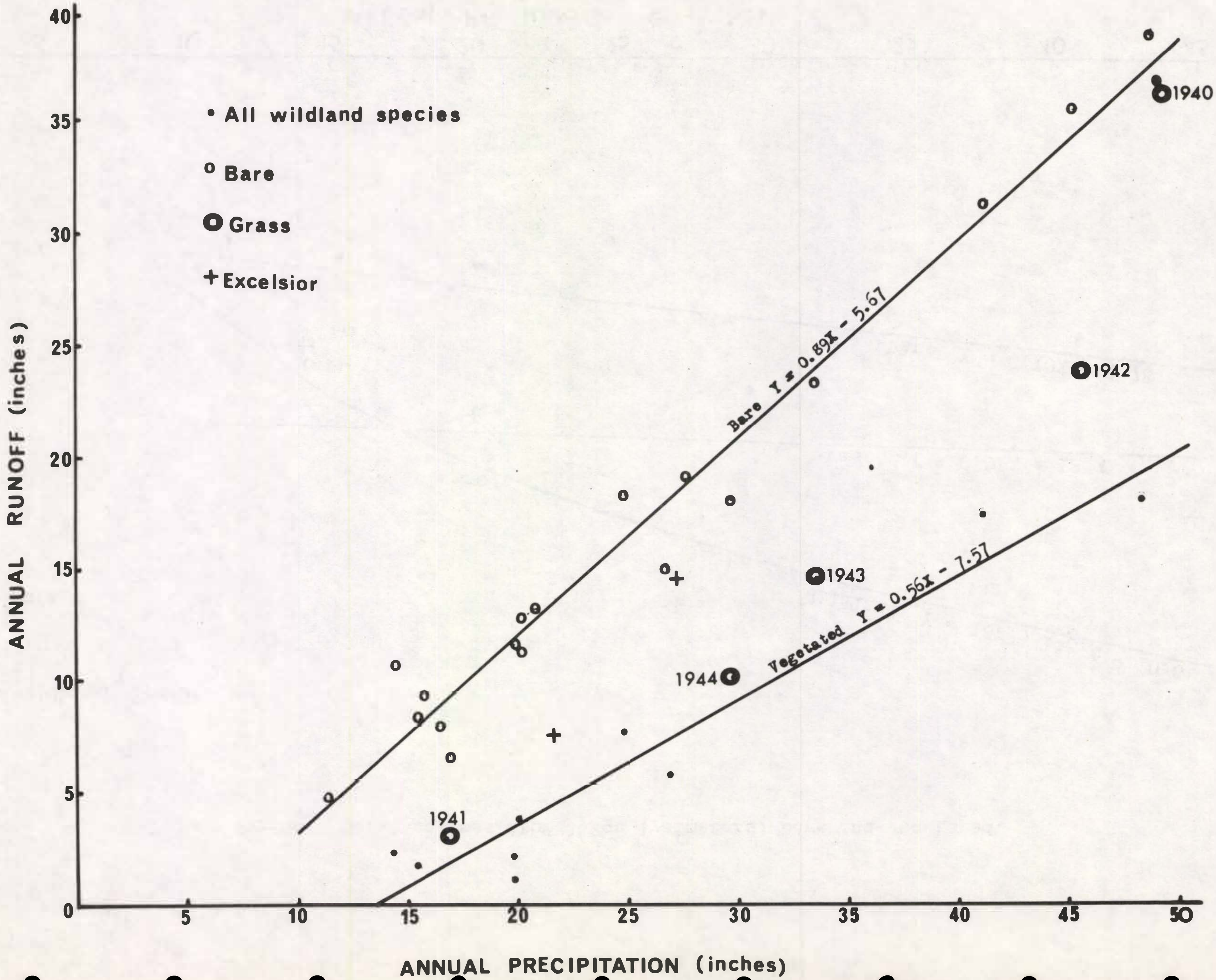


Figure 9.--Soil moisture loss from large lysimeters, bare and vegetated.

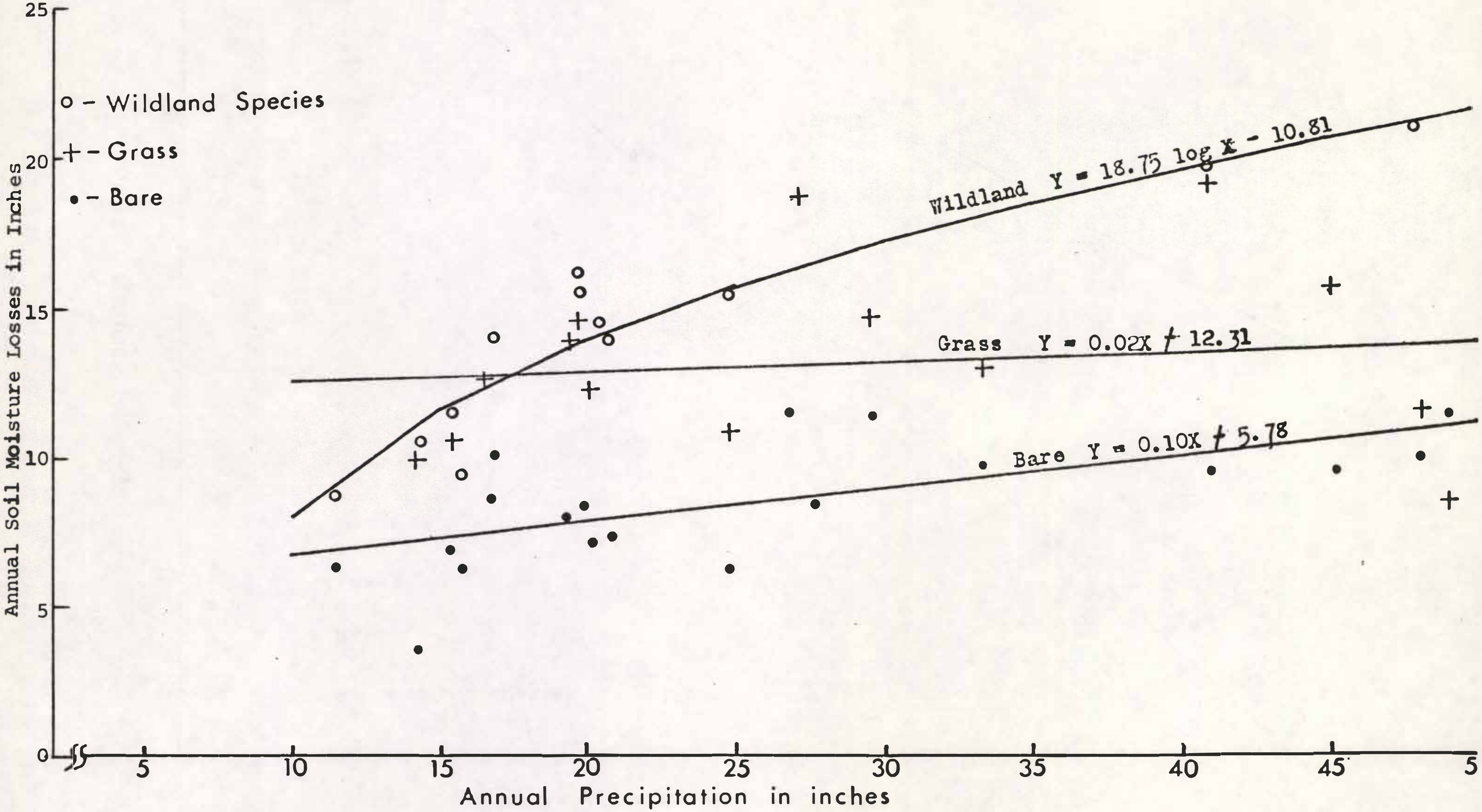


Figure 10.--Depth, duration, and severity of soil drying in the San Dimas large lysimeters. Darkest shading indicates soil moisture near field capacity, no shading indicates soil moisture near wilting point, and light shading an unspecified degree of water availability to plants between those extremes.

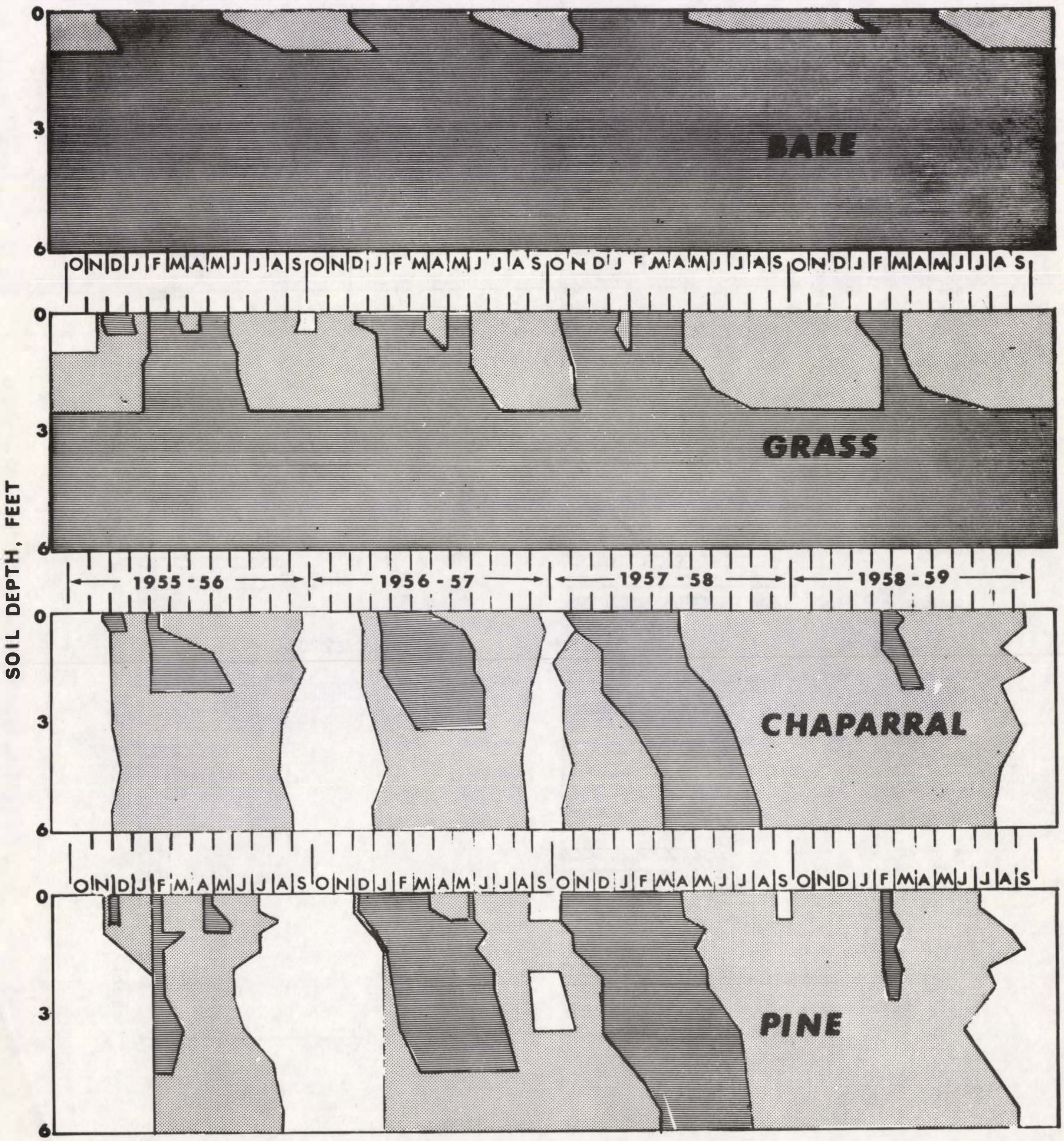


Figure 11.--Ratios of actual to potential evaporative losses for wet and dry years. For all lysimeters containing Colman units (large - 5, 9, 15, 19, and 24; unconfined - A, B, C, D, and E).

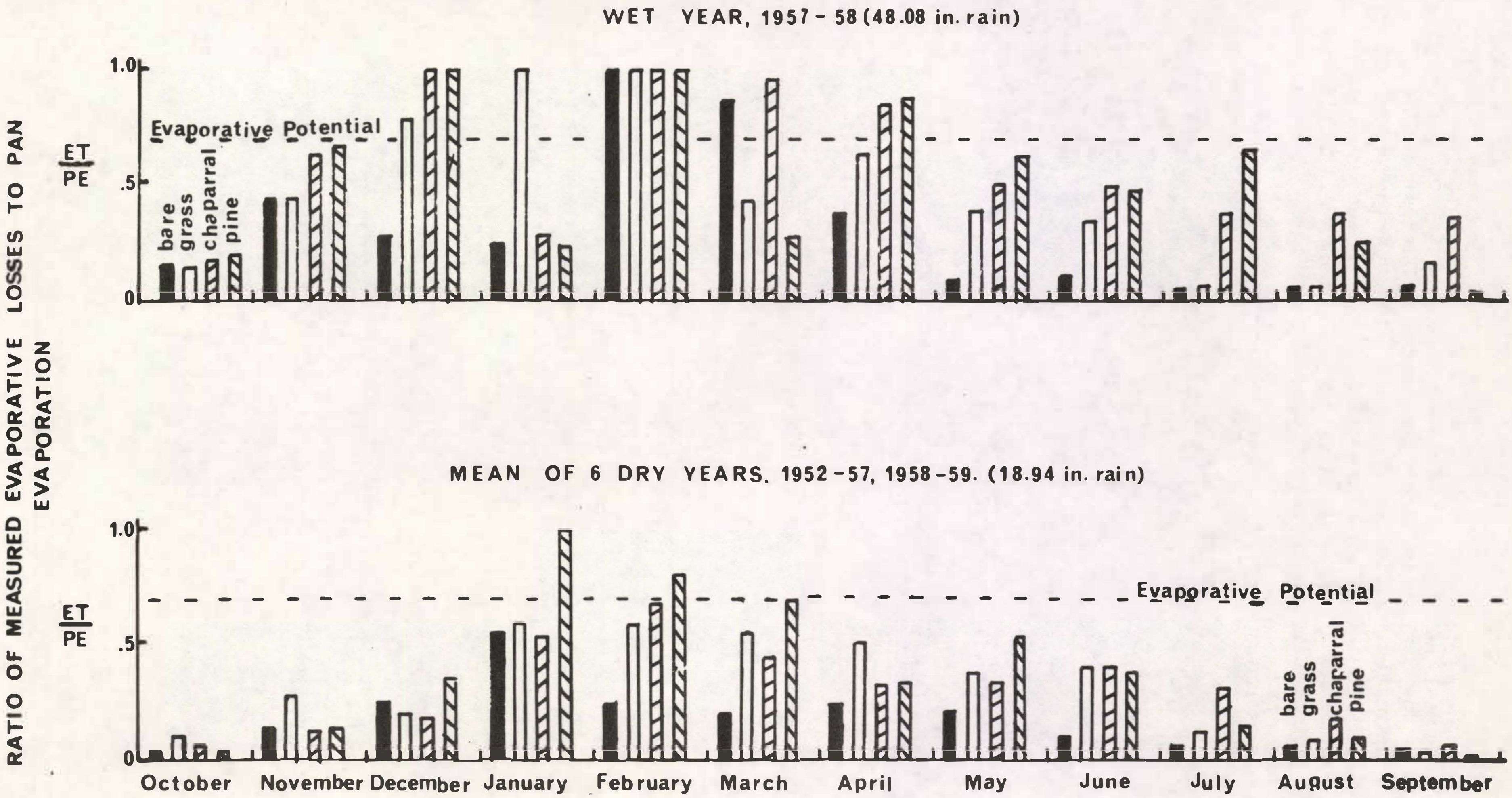
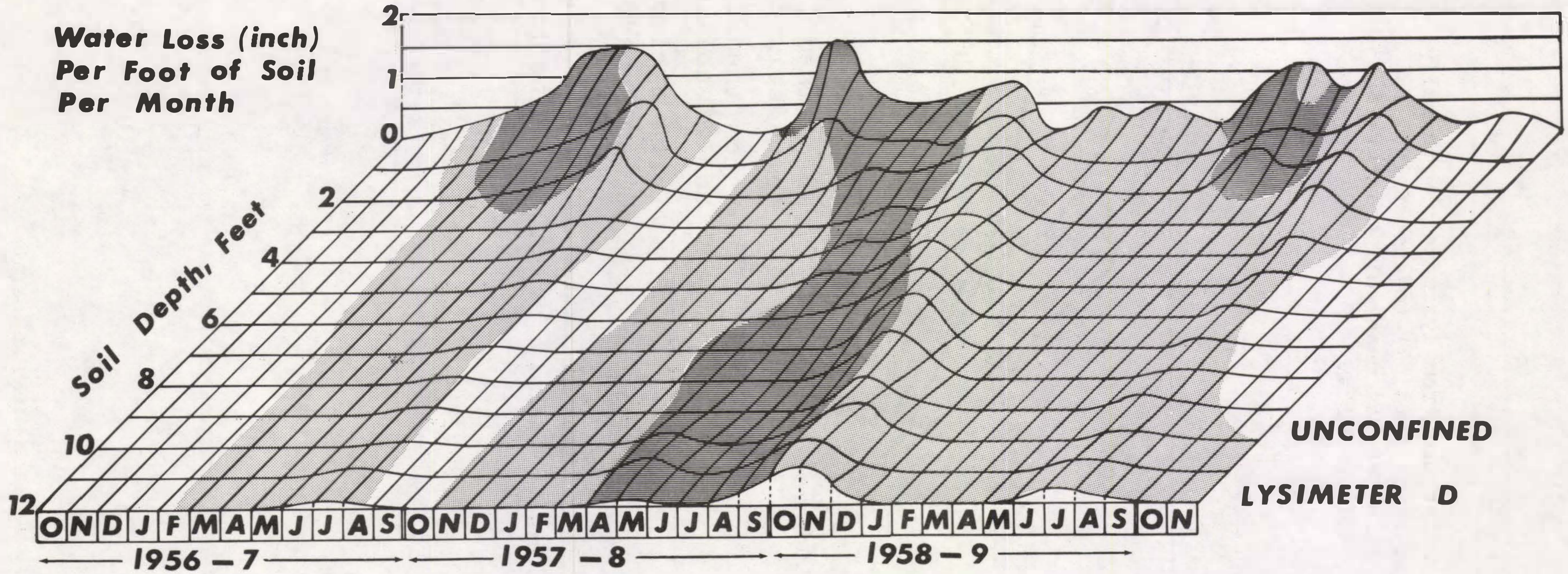


Figure 12.--Three years of water loss from deep and shallow lysimeter soils containing scrub oak. Shading indicates energy status of soil moisture as in Figure 10. Soil depths are 1 foot intervals; soil depth 0, for example, represents soil from 0 to 1 feet deep.



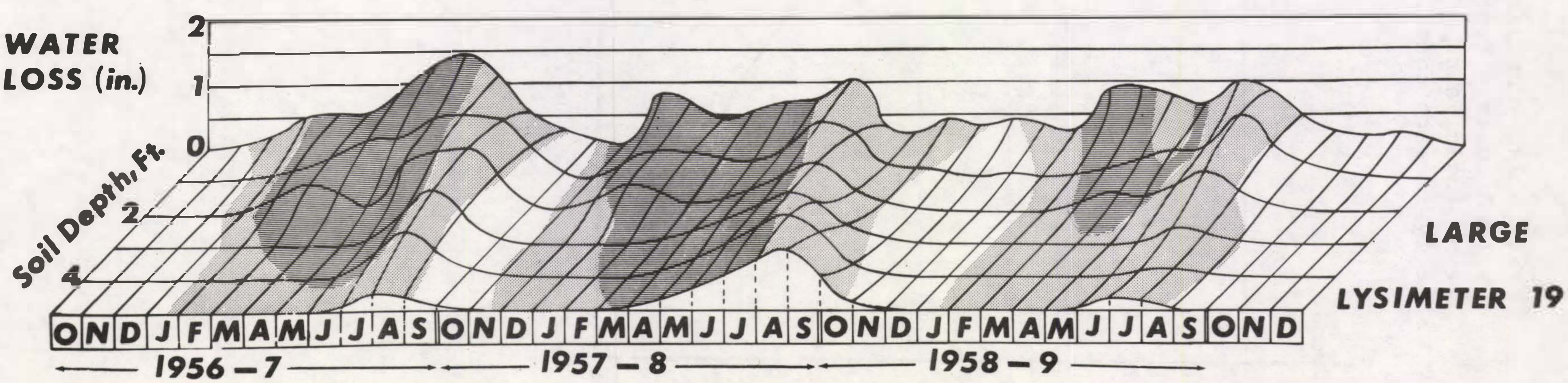


Figure 13.--Cumulative water use from lysimeters with fully wetted soils. From last rain (April 7) to end of 1957-58 hydrologic year. Each line depicts mean soil moisture from 5 lysimeters containing Colman units.

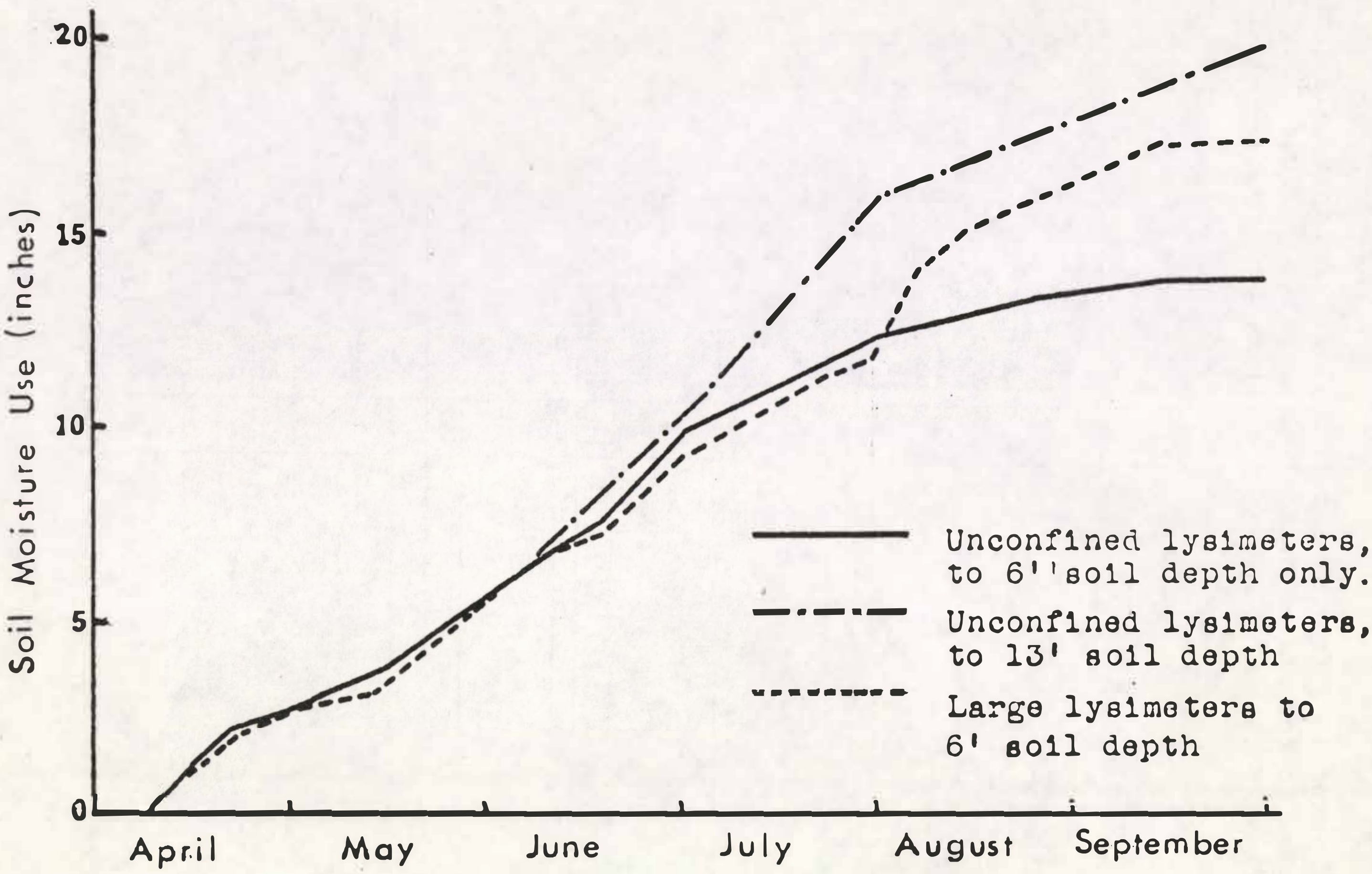


Figure 14.--Influence of vegetative cover on soil moisture losses from large (solid line) and unconfined lysimeters (dashed line).

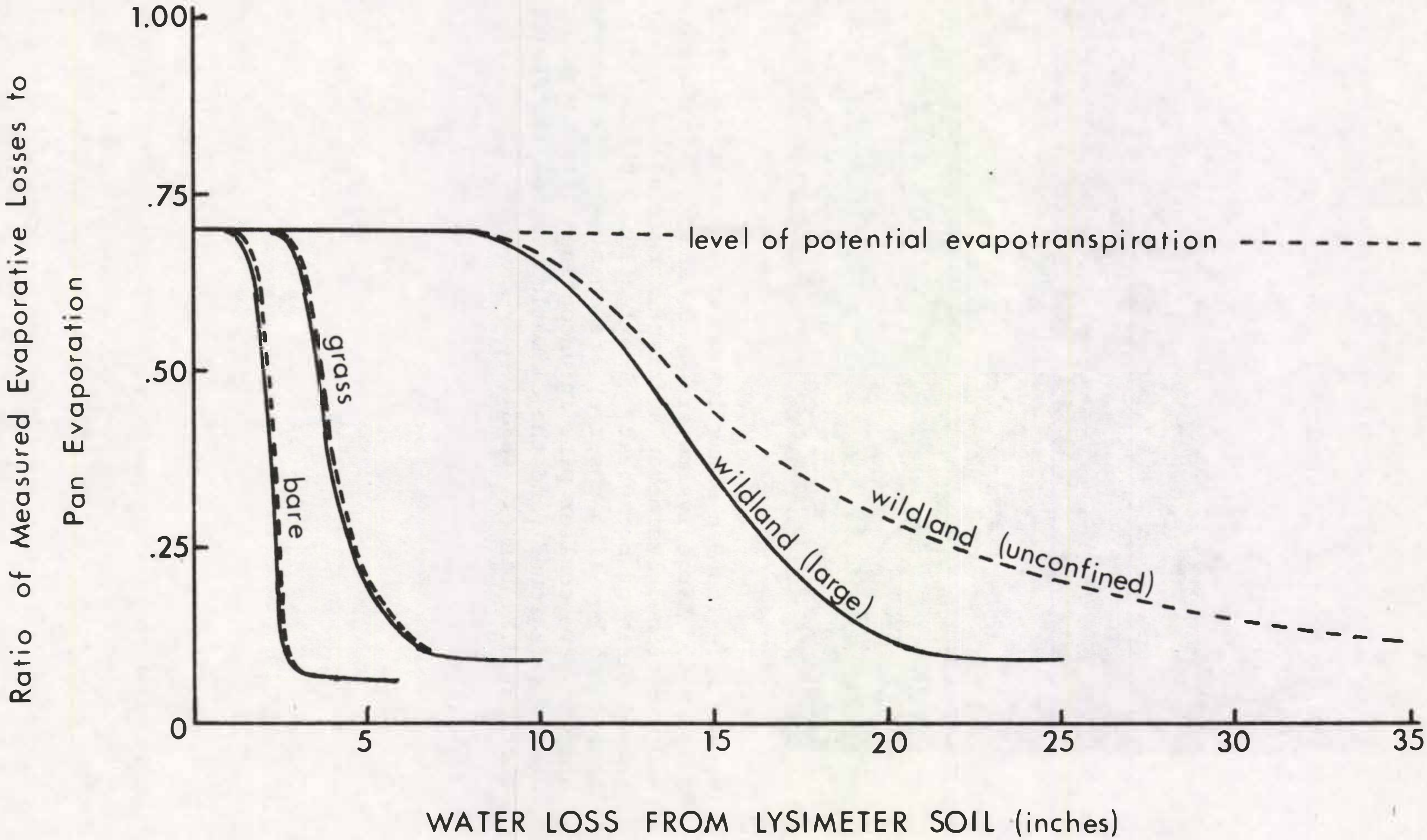


Figure 15.--The San Dimas lysimeters after the wildfire of July 1960. Large lysimeters 4, 5, and 6 (left foreground) and unconfined lysimeter A (right foreground) had been gurned clean of buckwheat. The leafless, blackened stems behind the kneeling observer are chamise. Firemen were able to save coulter pine in unconfined lysimeter E (right center background) and the climatic station (extreme right). Photo by J.E. Linder, USFS.